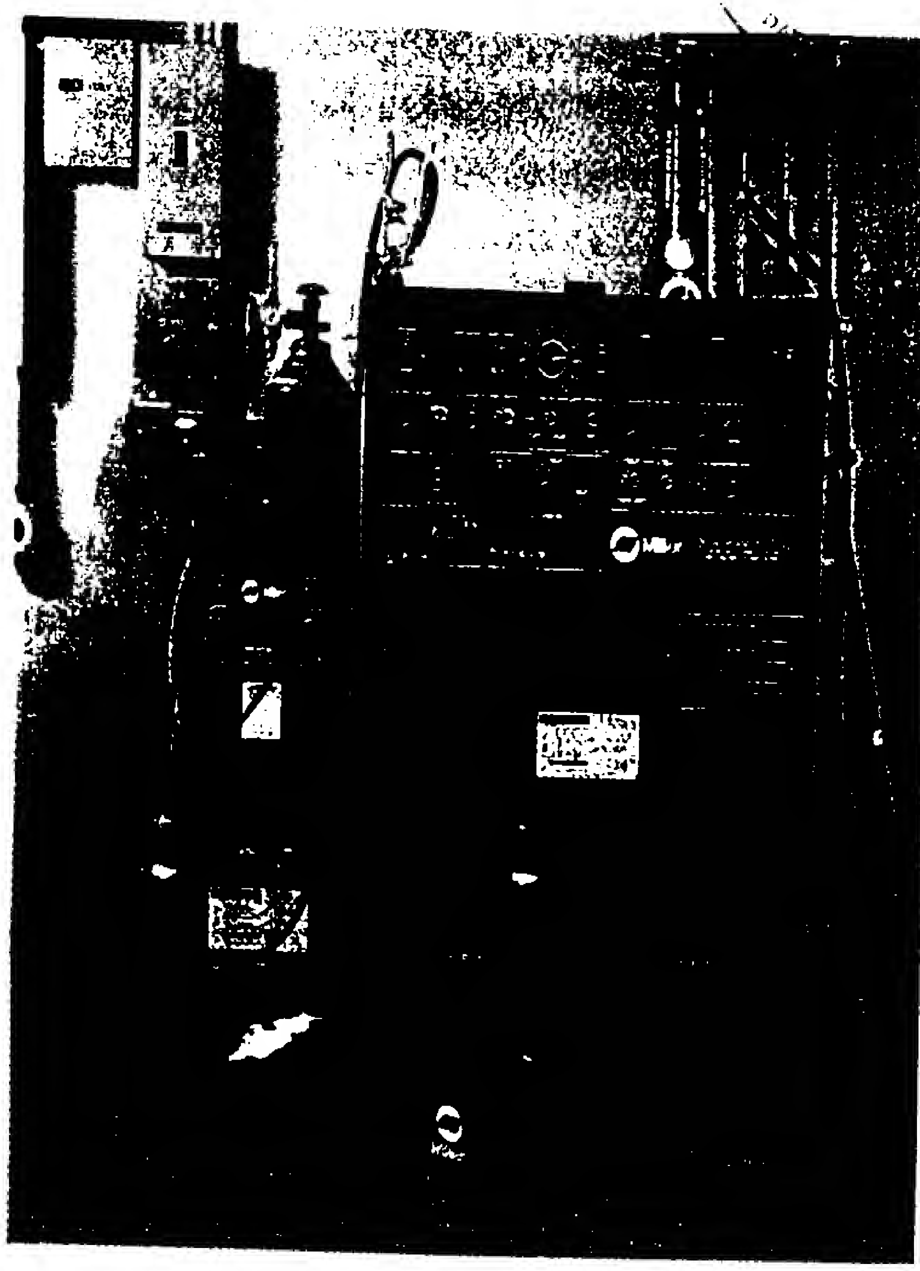


Figure 3.22 - Gas Tungsten Arc Welding Equipment

during the welding operation, a remote current control may also be attached. It can be foot-operated or controlled by some device mounted on the torch itself. This is particularly useful for welding thin materials and open root pipe joints, where instantaneous control is necessary.

There are numerous applications for GTAW in many industries. It is capable of welding virtually all materials, because the electrode is not melted during the welding operation. Its ability to weld at extremely low currents makes gas tungsten arc welding suitable for use on the thinnest (down to 0.005 inch) of metals. Its typically clean and controllable operation causes it to be the perfect choice for extremely critical applications such as those found in the aerospace, food and drug processing, petrochemical, and power piping industries.

The principal advantage of GTAW lies in the fact that it can produce welds of high quality and excellent visual appearance. Also, since no flux is used, the process is quite clean and there is no slag to remove after welding. As mentioned before, extremely thin sections can be welded. Due to the nature of its operation, it is suitable for welding most metals, many of which are not as easily welded using other welding processes. If joint design permits, these materials can be welded without the use of additional filler metal.

When required, numerous types of filler metals exist in wire form for a wide range of metal alloys. In the case where there is no commercially-available wire for a particular metal alloy, it is possible to produce a suitable filler metal by simply shearing a piece of identical base metal to produce a narrow piece which can be hand-fed into the weld zone just as if it were a wire.

Contrasting these advantages are several disadvantages. First, GTAW is among the slowest of the available welding processes. While it produces a clean weld deposit, it is also characterized as having a low tolerance for contamination. Therefore, base and filler metals must be extremely clean prior to welding. When used as a manual process, gas tungsten arc welding requires a high skill level; the welder must coordinate the arc with one hand while feeding the filler metal with the other. GTAW is normally selected in situations where the need for very high quality warrants additional cost to overcome these limitations.

One of the inherent problems associated with this method has to do with its inability to tolerate contamination. If contamination or moisture is encountered, whether from the base metal, filler metal or shielding gas, the result could be porosity in the deposited weld. When porosity is noted, this is a sign that the process is out of control and some preventive measures are necessary. Checks should be made to determine the source of the contamination so that it can be eliminated.

Another inherent problem which is almost totally confined to the GTAW process is that of tungsten inclusions. As the name implies, this discontinuity occurs when pieces of the tungsten electrode become included in the weld deposit. Tungsten inclusions can occur due to a number of reasons, and several are listed in the following table.

Reasons for Tungsten Inclusions.

1) Contact of electrode tip with molten metal;
2) Contact of filler metal with hot tip of electrode;
3) Contamination of the electrode tip by spatter;
4) Exceeding the current limit for a given electrode diameter or type;
5) Extension of electrodes beyond their normal distances from the collet, resulting in over-heating of the electrode;
6) Inadequate tightening of the collet;
7) Inadequate shielding gas flow rates or excessive wind drafts resulting in oxidation of the electrode tip;
8) Defects such as splits or cracks in the electrode;
9) Use of improper shielding gases; and
10) Improper grinding of the electrode tip.

Submerged Arc Welding (SAW)

The last of the more common welding processes to be discussed is submerged arc welding. This method is typically the most efficient one mentioned so far in terms of the rate of weld metal deposition. SAW is characterized by the use of a continuously-fed solid wire electrode which provides an arc that is totally covered by a layer of granular flux; hence the name "submerged" arc. Figure 3.23 shows how a weld is produced using this process.

As mentioned, the wire is fed into the weld zone much the same way as with gas metal arc welding or flux cored arc welding. The major difference, however, is in the method of shielding. With submerged arc welding, a granular flux is distributed ahead of or around the wire electrode to facilitate the protection of the molten metal. As the welding progresses, in addition to the weld bead, there is a layer of formed slag and still-granular flux covering the solidified weld metal. The slag must be removed and is usually discarded, although there are techniques for recombining a portion of it with new flux for reuse in some applications. The still-granular flux can be recovered and reused if care is taken to prevent its contamination. In some cases where the flux must provide alloying for the weld, reuse of the flux may not be advisable.

Since SAW uses a separate electrode and flux, there are numerous combinations available for specific applications. There are two general types of combinations which can be used to provide an alloyed weld deposit; an alloy electrode with a neutral flux, or a mild steel electrode with an alloy flux. Therefore, to properly describe the filler material for SAW, the American Welding Society identification system consists of designations for both the electrode and flux. Figure 3.24 shows what the various parts of the electrode/flux classification system actually signify, with an actual example.

The equipment used for submerged arc welding consists of several components, as

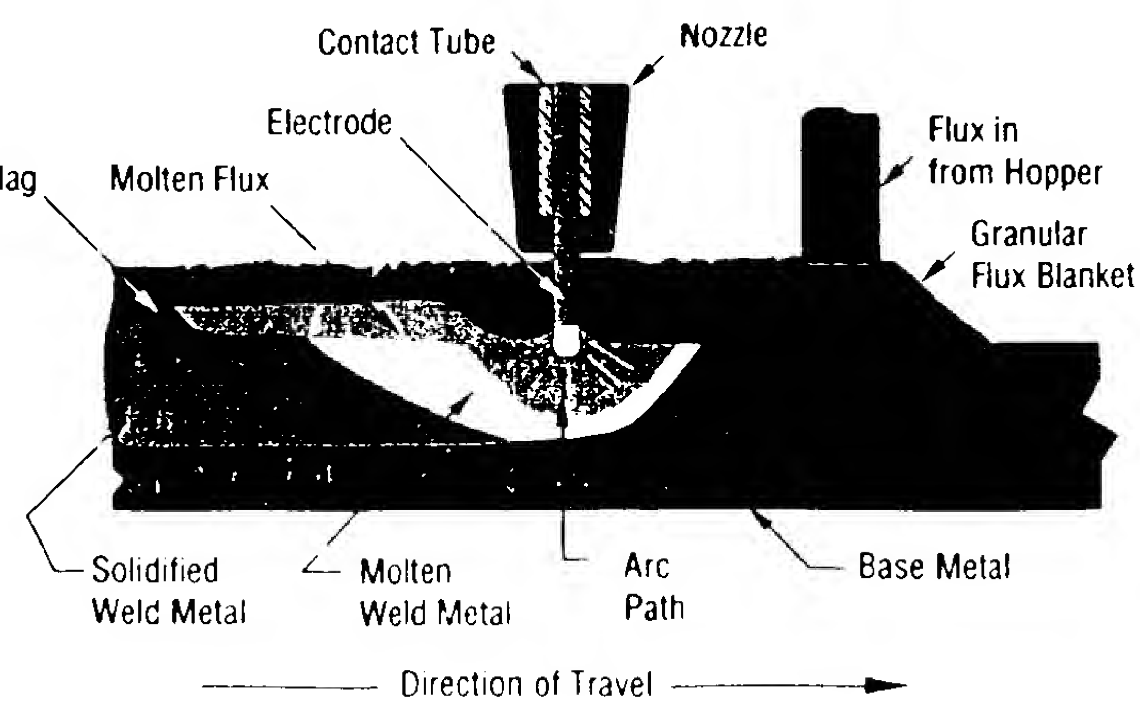


Figure 3.23 - Submerged Arc Welding

Indicates flux

Indicates the minimum tensile strength (in increments of 10 000 psi (69 MPa) of weld metal made in accordance with the welding conditions given, and using the flux being classified and the specific classification of electrode indicated.

Designates the condition of heat treatment in which the tests were conducted: •A• for the as-welded and •P• for postweld heat treated. The time and temperature of the PWHT are as specified.

Indicates the lowest temperature at which the impact strength of the weld metal referred to above meets or exceeds 20 ft-lb (27J).

E indicates a solid electrode; EC indicates a composite electrode.

FXXX-EXXX

Classification of the electrode used in producing the weld referred to above.

Examples

F7A6-EM12K is a complete designation. It refers to a flux that will produce weld metal which, in the as-welded condition, will have a tensile strength no lower than 70 000 psi (480 MPa) and Charpy V-notch impact strength of a least 20 ft-lb (27 J) at -60°F (-51°C) when produced with an EM12K electrode under the conditions called for in this specification.

F7A4-EC1 is a complete designation for a flux when the trade name of the electrode used in the classification is indicated as well. It refers to a flux that will produce weld metal with that electrode, which in the as-welded condition, will have a tensile strength no lower than 70 000 psi (480 MPa) and Charpy V-notch of at least 20 ft-lb (27 J) at -40°F (-40°C) under the conditions called for in this specification

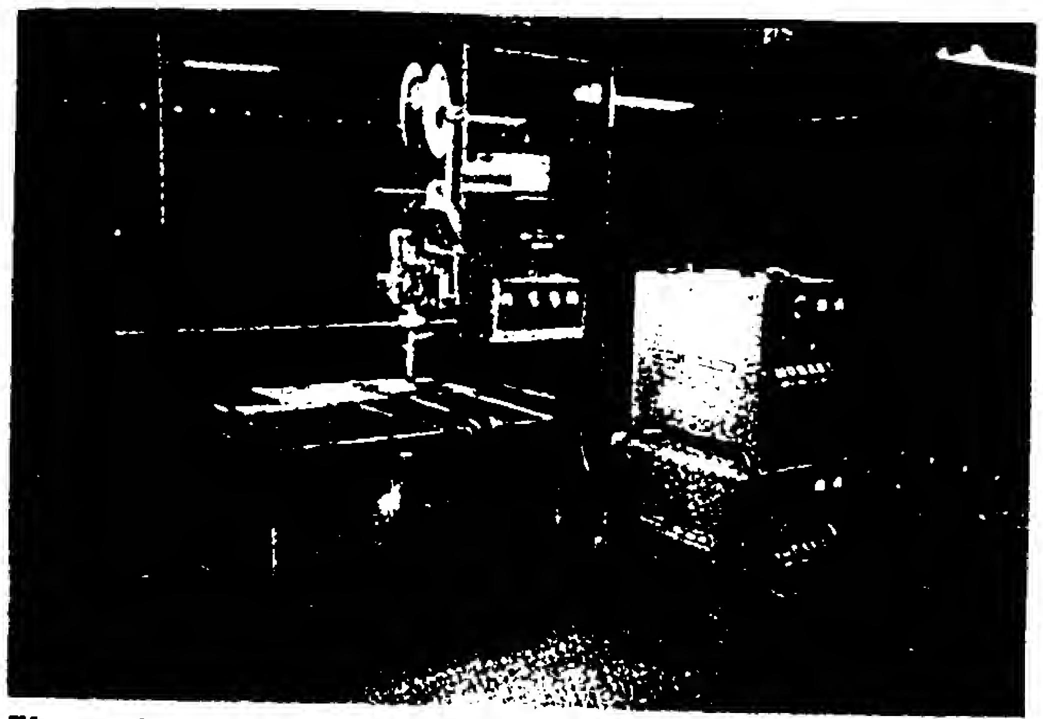
Figure 3.24 - SAW Filler Metal Identification System

shown in Figure 3.25. Since this process can be used as a fully mechanized or semiautomatic method, the equipment used for each is slightly different. In either case, however, some power source is required. Although most submerged arc welding is performed with a constant voltage power source, there are certain applications where a constant current type is preferred. As with gas metal arc welding and flux cored arc welding, a wire feeder forces the wire through the cable liner to the welding torch.

The flux must be moved to the weld zone; for mechanized systems, the flux is generally placed into a hopper above the welding torch and fed by gravity so that it is distributed either slightly ahead of the arc or around the arc from a nozzle surrounding the contact tip. In the case of semiautomatic submerged arc welding, the flux is forced to the gun using compressed air which 'fluidizes' the granular flux, causing it to flow easily, or there is a hopper connected directly to the hand-held gun.

Another equipment variation is the choice of alternating or direct current, either polarity. The type of welding current will affect both penetration and weld bead contour. For some applications, multiple electrodes can be used. The electrodes may be energized by a single power source, or multiple power sources may be necessary. The use of multiple electrodes provides even more versatility for the process.

SAW has found acceptance in many industries, and it can be performed on numerous metals. Due to the high rate of weld metal deposition, it has shown to be quite effective for overlaying or building up material surfaces. In situations where a surface needs improved



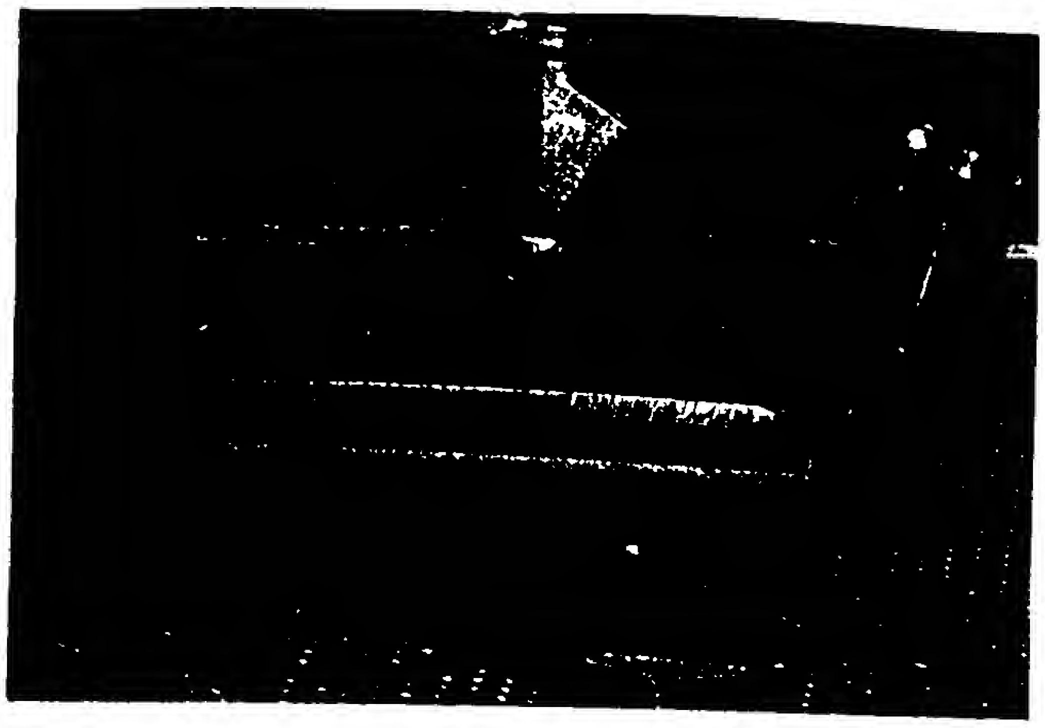


Figure 3.25 - Submerged Arc Welding Equipment

corrosion or wear resistance, it is often more economical to cover a susceptible base metal with a resistant weld overlay. If this application can be mechanized, submerged arc welding is an excellent choice.

Probably the biggest advantage of SAW is its high deposition rate. It can typically deposit weld metal more efficiently than any of the more common processes. The submerged arc welding process also has high operator appeal, first because of the lack of a visible arc which allows the operator to control the welding without the need for a filter lens and other heavy protective clothing. The other beneficial feature is that there is less smoke generated than with some of the other processes. Another feature of the process which makes it desirable for many applications is its ability to penetrate deeply.

The major limitation of SAW is that it can only be done in a position where the flux can be supported in the weld joint. When welding in a position other than the normally-used flat or horizontal fillet positions, some device is required to hold the flux in place so it can perform its job. Another limitation is that, like most mechanized processes, there may be a need for extensive fixturing and positioning equipment. As with other processes using a flux, finished welds have a layer of solidified slag which must be removed.

If welding parameters are improper, weld contours could be such that this job of slag removal is even more difficult. The final disadvantage relates to the flux which covers the arc during welding. While it does a good job of protecting the welder from the arc, it also prevents the welder from seeing exactly where the arc is positioned with respect to the joint. With a mechanized setup, it is advisable to track the entire length of the joint without the arc or the flux to check for alignment. If the arc is not properly directed, incomplete fusion can result.

There are some inherent problems related to SAW. The first has to do with the granular flux. Just as with low hydrogen SMAW electrodes, it is necessary to protect the submerged arc welding flux from moisture. It may be necessary to store the flux in heated containers prior to use. If the flux becomes wet, porosity and underbead cracking may result.

Another characteristic problem of SAW is solidification cracking. This results when the welding conditions provide a weld bead having an extreme width-to-depth ratio. That is, if the bead's width is much greater than its depth, or vice versa, centerline shrinkage cracking could occur during solidification. Figure 3.26 shows some conditions which could cause cracking.

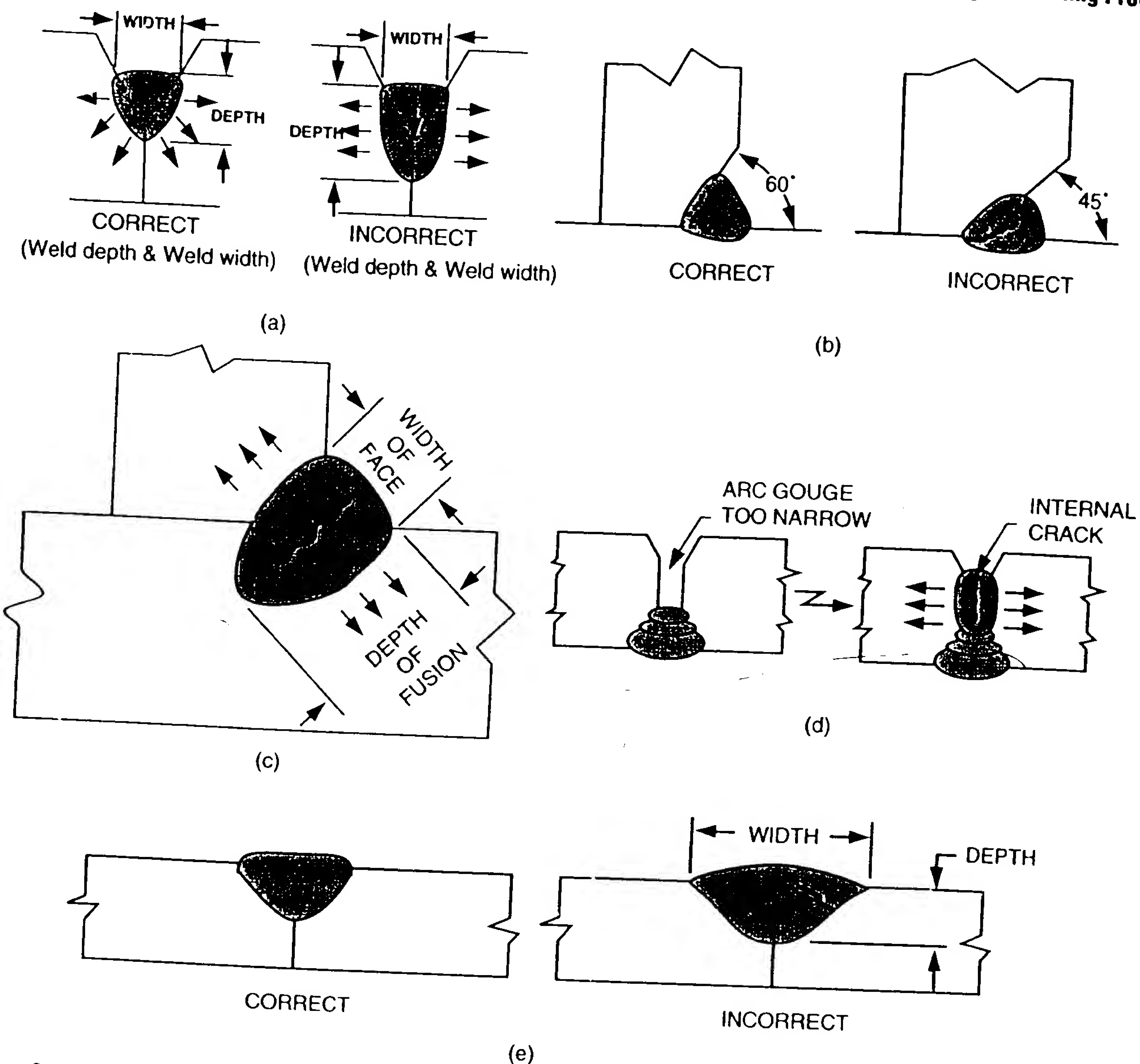


Figure 3.26 - Solidification Cracking Because of Weld Profile

Plasma Arc Welding (PAW)

The next process to be discussed is plasma arc welding. A plasma is defined as an ionized gas. With any process using an arc, a plasma is created. However, PAW is so named because of the intensity of this plasma region. At first glance, PAW could be easily mistaken for GTAW because the equipment required is quite similar. A typical setup is shown in Figure 3.27.

Both GTAW and PAW use the same type of power source. However, when we look closely at the torch itself, the difference becomes more obvious. Figure 3.28 shows a graphic comparison of the two types of welding torches and the resulting difference in the amount of heating, and therefore penetration, which will occur.

Both the PAW and GTAW torches use a tungsten electrode for the creation of the arc. However, with the PAW torch, there is a copper orifice within the ceramic nozzle. There is a high velocity "plasma" gas which is forced

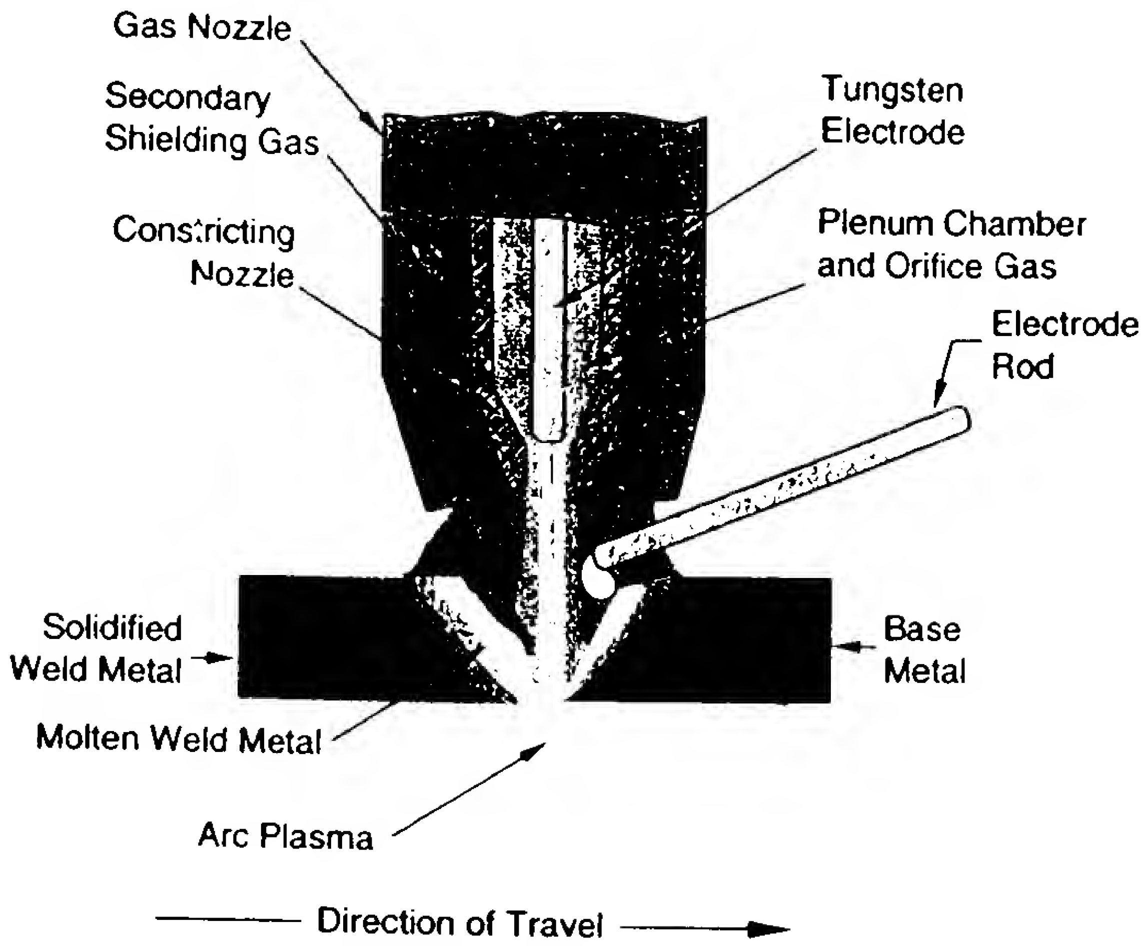


Figure 3.27 - Plasma Arc Welding

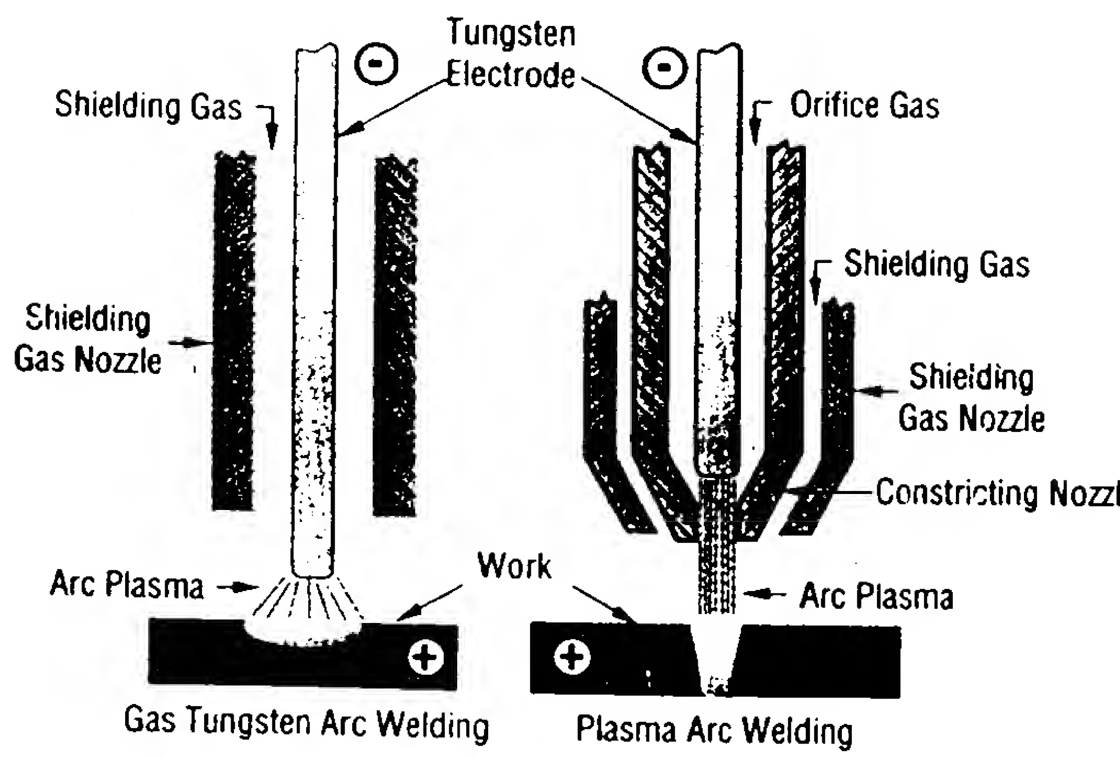


Figure 3.28 - Comparison of GTAW and PAQ Torches

through this orifice and past the welding arc resulting in the constriction of the arc.

This constriction, or squeezing, of the arc causes it to be more concentrated, and therefore more intense. One way to illustrate the difference in arc intensity between GTAW and PAW would be to use the analogy of an adjustable water hose nozzle. The GTAW arc would be comparable to the gentle mist setting, while the PAW arc would behave more like the setting which provides a concentrated stream of water having a greater force.

There are two categories of plasma arc operation, the transferred and nontransferred arc. They are shown in Figure 3.29.

With the transferred arc, the arc is created between the tungsten electrode and the workpiece. The nontransferred arc, on the other hand, occurs between the tungsten electrode and the copper orifice. The transferred arc is generally used for both welding and cutting of conductive materials, because it results in the greatest amount of heating of the workpiece. The nontransferred arc is preferred for the cutting of nonconductive materials and for welding of materials when the amount of heating of the workpiece must be minimized.

The similarities between GTAW and PAW extend to the equipment as well. The power sources are identical in most respects. However, as shown in Figure 3.30, there are some additional elements necessary, including the plasma control console and a source of plasma gas.

The torch, as discussed above, does differ slightly; however, a careful check of the internal configuration must be made to be certain. Figure 3.31 illustrates some of the internal

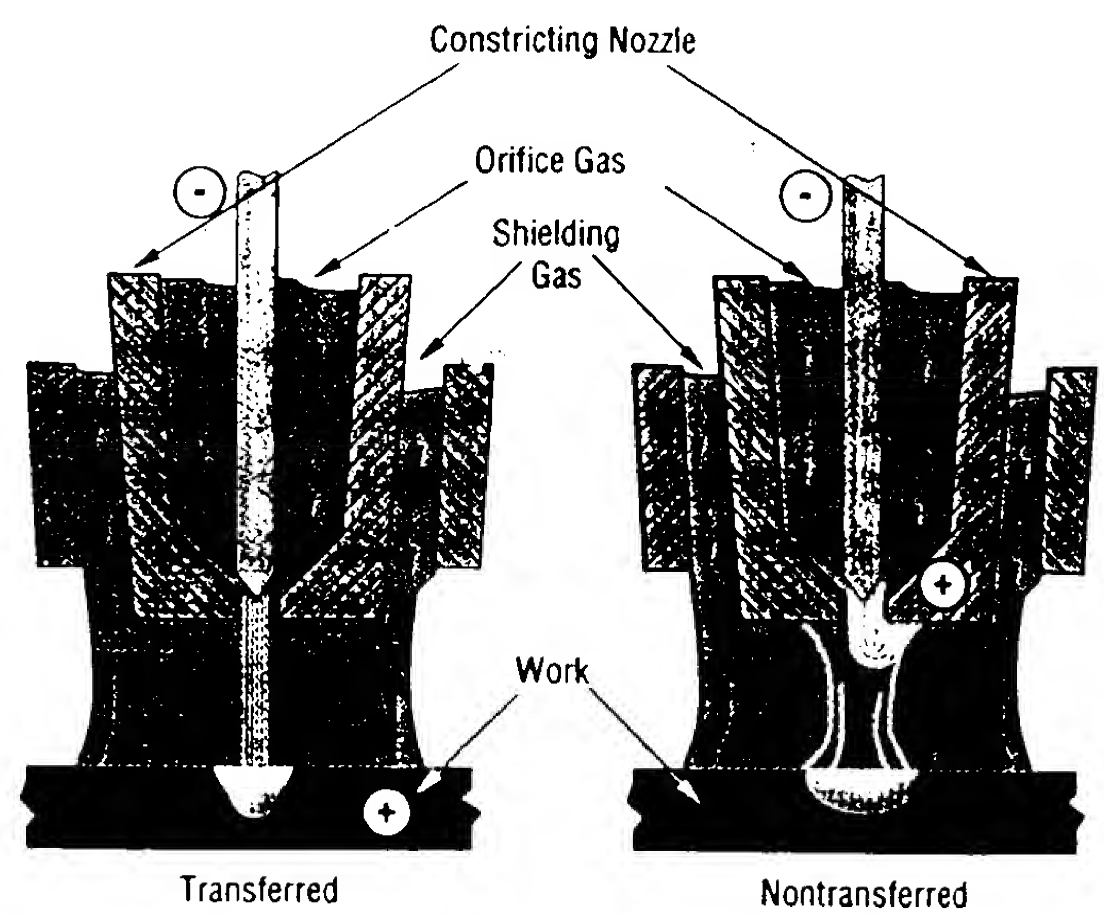
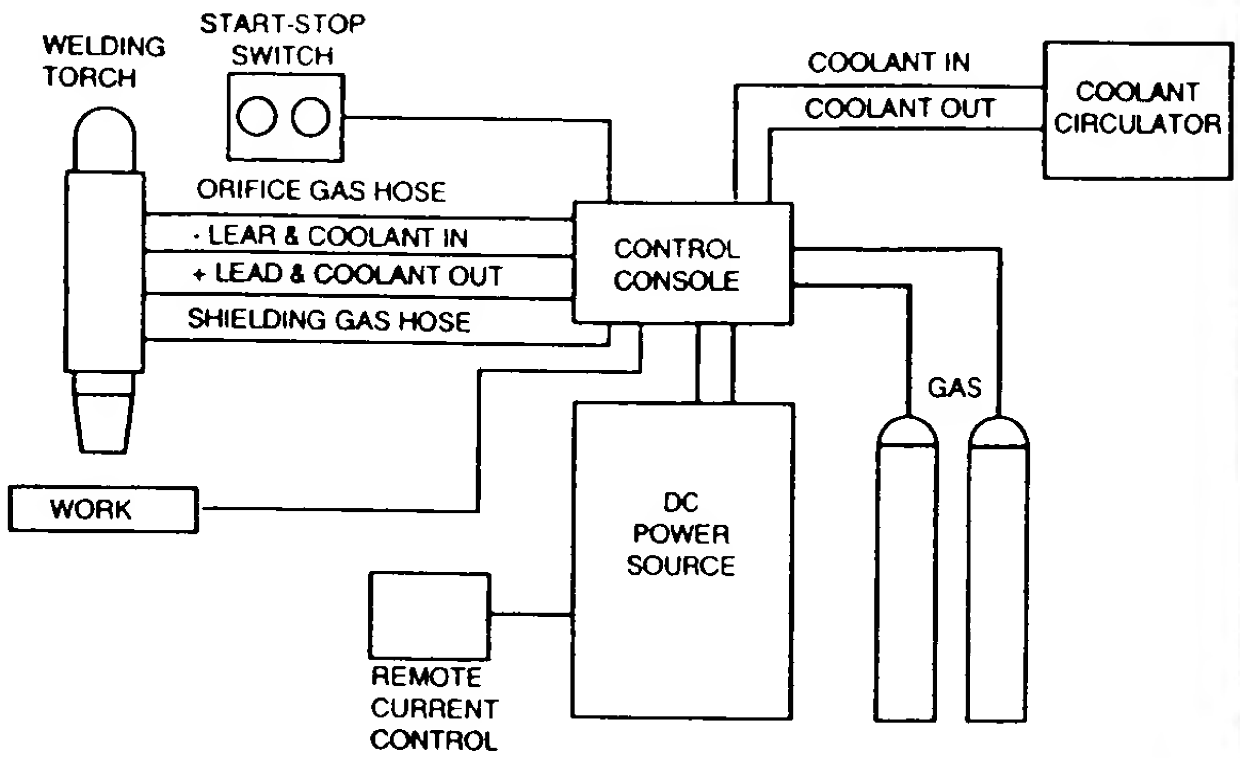


Figure 3.29 - Transferred and Nontransferred PAW Comparison



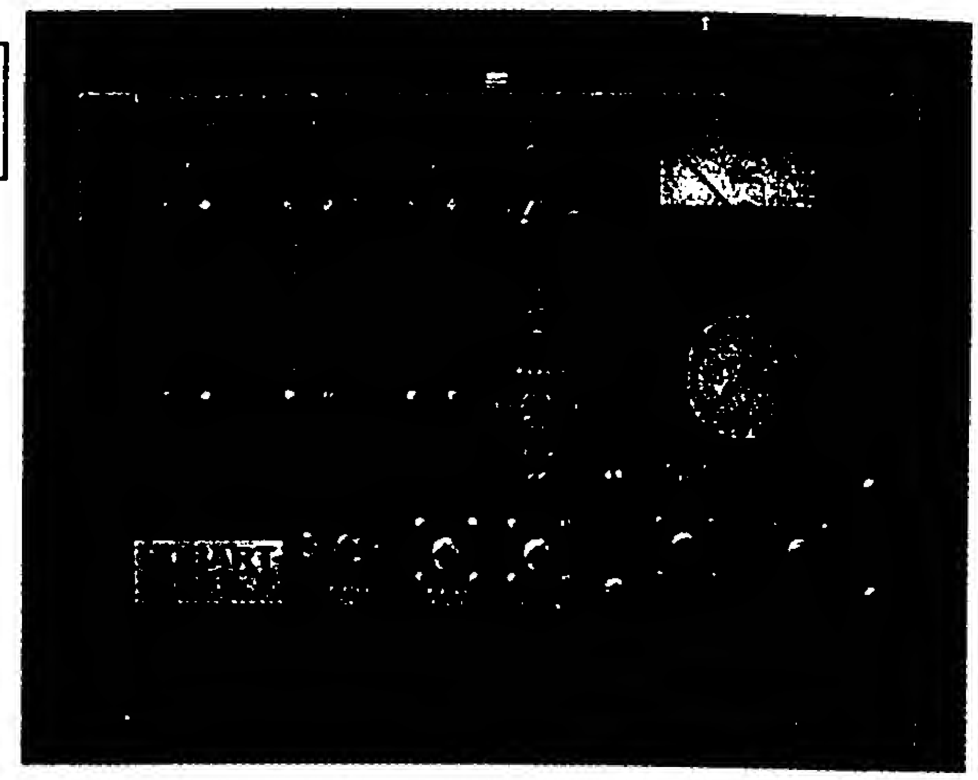


Figure 3.30, Plasma Arc Welding Equipment

welding.

As indicated, two separate gases are required: the shielding gas and the orifice (or plasma) gas. Argon is most commonly employed for both types of gas. However, welding of various metals might warrant the use of helium or combinations of argon/helium or argon/hydrogen for one or the other gases.

The primary applications for PAW are similar to those for GTAW. PAW is used for the same materials and thicknesses. PAW becomes the choice where applications warrant the use of a more localized heat source. It is used extensively for full penetration welds in material up to 1/2 inch thick by employing a technique referred to as "keyhole welding". Figure 3.32 shows the typical appearance of a keyhole weld.

Keyhole welding is performed on a square butt joint with no root opening. The concentrated heat of the arc penetrates through the material thickness to form a small keyhole. As welding progresses, the keyhole moves along the joint melting the edges of the base metal which then flow together and solidify after the welding arc passes. This creates a high quality weld, with no elaborate joint preparation and fast travel speeds compared to GTAW.

One advantage of PAW, which was mentioned before, is that it provides a very localized heat source. This allows for faster welding speeds and therefore less distortion. Since the standoff used between the torch end and the workpiece is typically quite long, the welder has better visibility of the weld being made. Also, since the tungsten electrode is recessed within the torch, the welder is less likely to stick it into the molten metal and produce a tungsten inclusion.

The ability to use this process in a keyhole mode is also desirable. The keyhole is a positive indication of complete penetration and

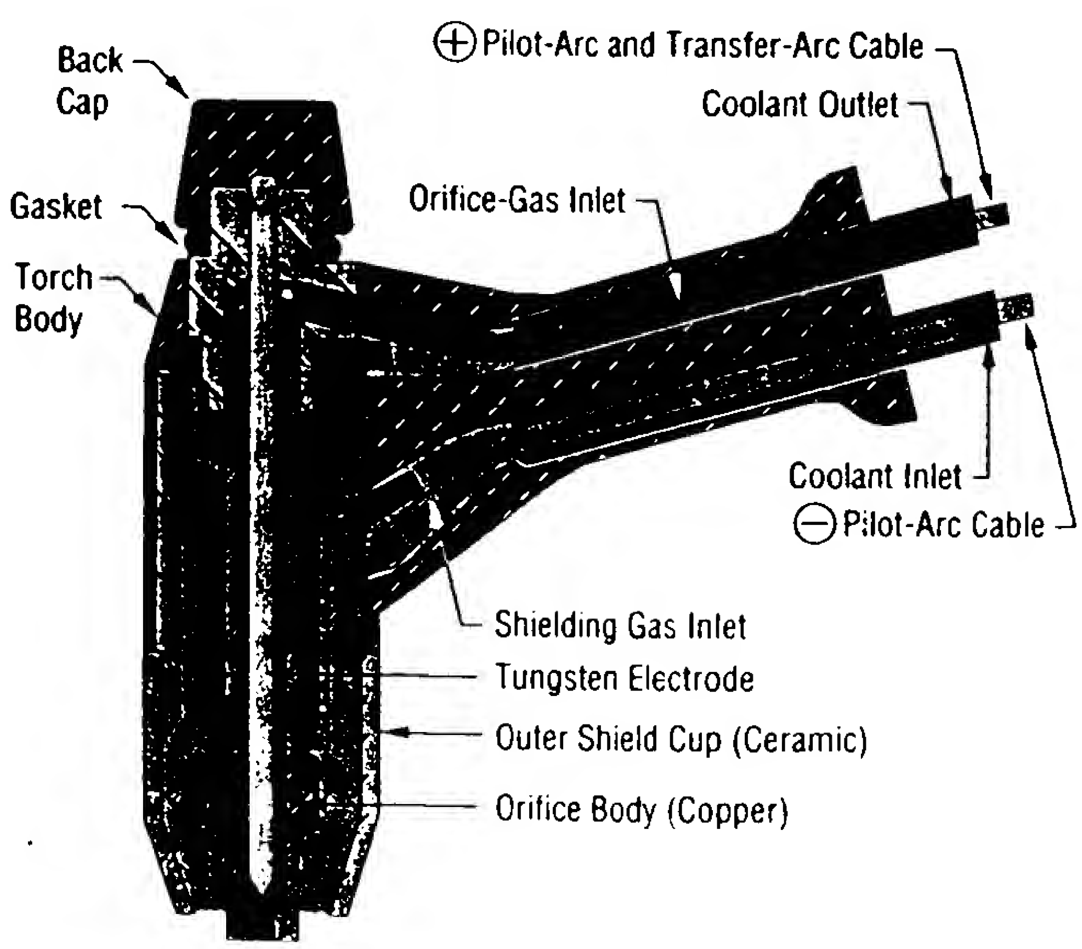


Figure 3.31 - Internal Structure of a Typical Manual PAW Torch

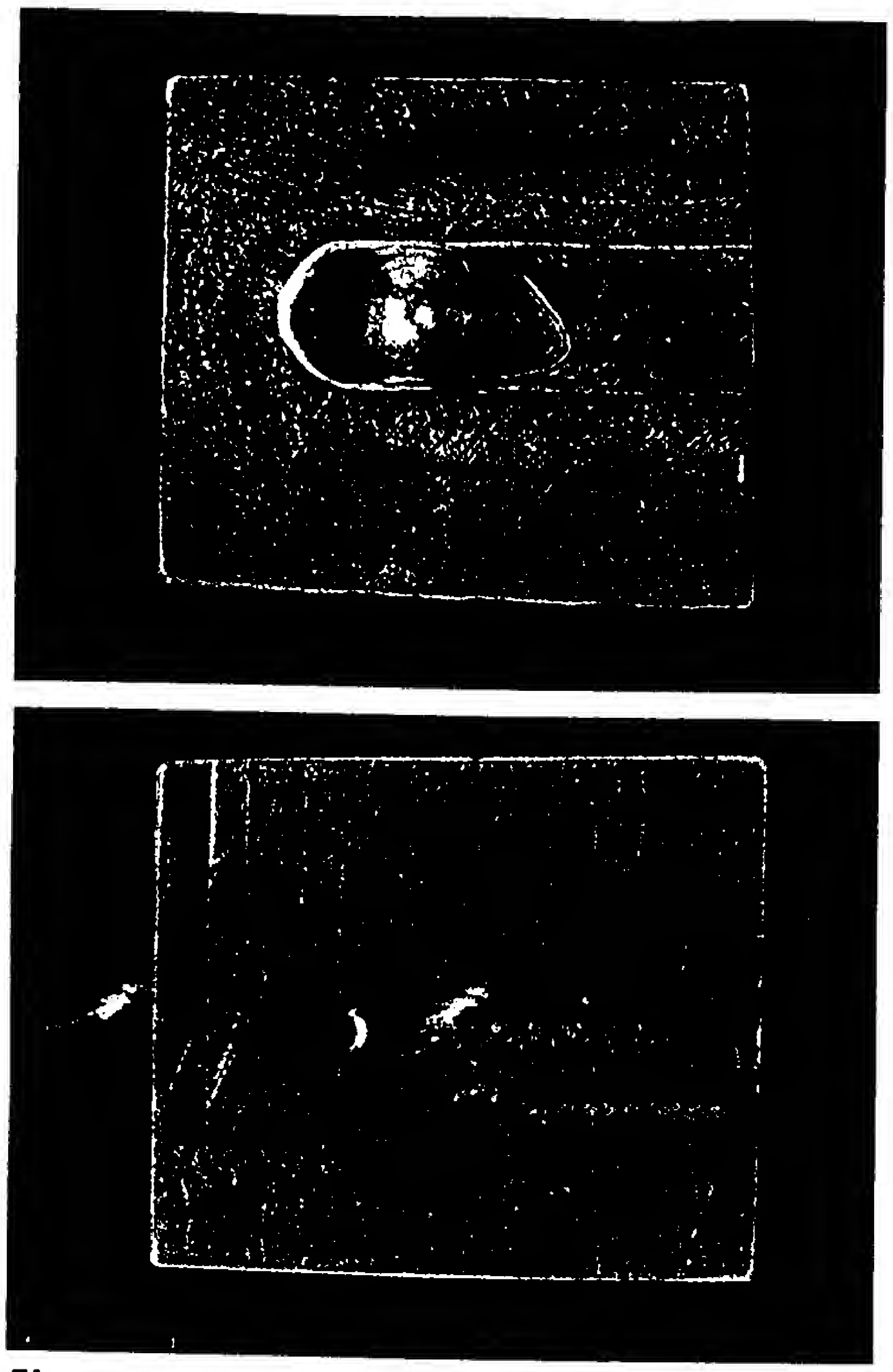


Figure 3.32 - Keyhole Technique for Plasma Arc Welding (Face - top and Root - bottom)

weld uniformity. This weld uniformity is in part due to the fact that plasma arc welding is less sensitive to changes in arc length. The presence of its collimated arc will permit relatively large changes in torch-to-work distance without any change in its melting capacity.

PAW is limited to the effective joining of materials 1 inch or less in thickness. The initial cost of the equipment is greater than that for GTAW, primarily because there is additional apparatus required. Finally, the use of PAW may require greater operator skill than would be the case for GTAW due to the more complex equipment setup.

Among the problems that may be encountered with this process are two types of metal inclusions. Tungsten inclusions may result from too-high current levels; however, the fact that the tungsten is recessed helps to prevent this occurrence. Too-high current could also result in the copper orifice melting and being deposited in the weld metal. Another problem that may be encountered when keyhole welding is being done is referred to as 'tunneling'. This occurs when the keyhole is not completely filled at the end of the weld, leaving a cylindrical void which may extend entirely through the throat of the weld. When using the keyhole technique, there is also a possibility of getting incomplete fusion since the arc and joint are so narrow. As a result, even small amounts of mistracking can produce incomplete fusion along the joint.

Electroslag Welding (ESW)

The next process of interest is electroslag welding, but it is not nearly as commonly used as the processes mentioned previously. It typically exhibits the highest deposition rate of any of the welding processes. ESW is characterized by the joining of members which are placed edge to edge so that the joint is vertical. The welding is done in a single pass such that the progression is from the bottom to the top of the joint, without interruption. Even though the welding progresses vertically up the joint, the position of welding is considered flat due to the location of the electrode with respect to the puddle. During welding, the molten metal is supported on two sides by water cooled shoes. See Figure 3.33.

An interesting feature of ESW is that it is not considered to be an arc welding process. It relies on heating from the electrical resistance of the molten flux to melt the base and filler metals. The process does use an arc to initiate the operation; however, that arc is extinguished once there is sufficient flux melted to provide the heating to maintain the welding operation as it progresses upward along the joint.

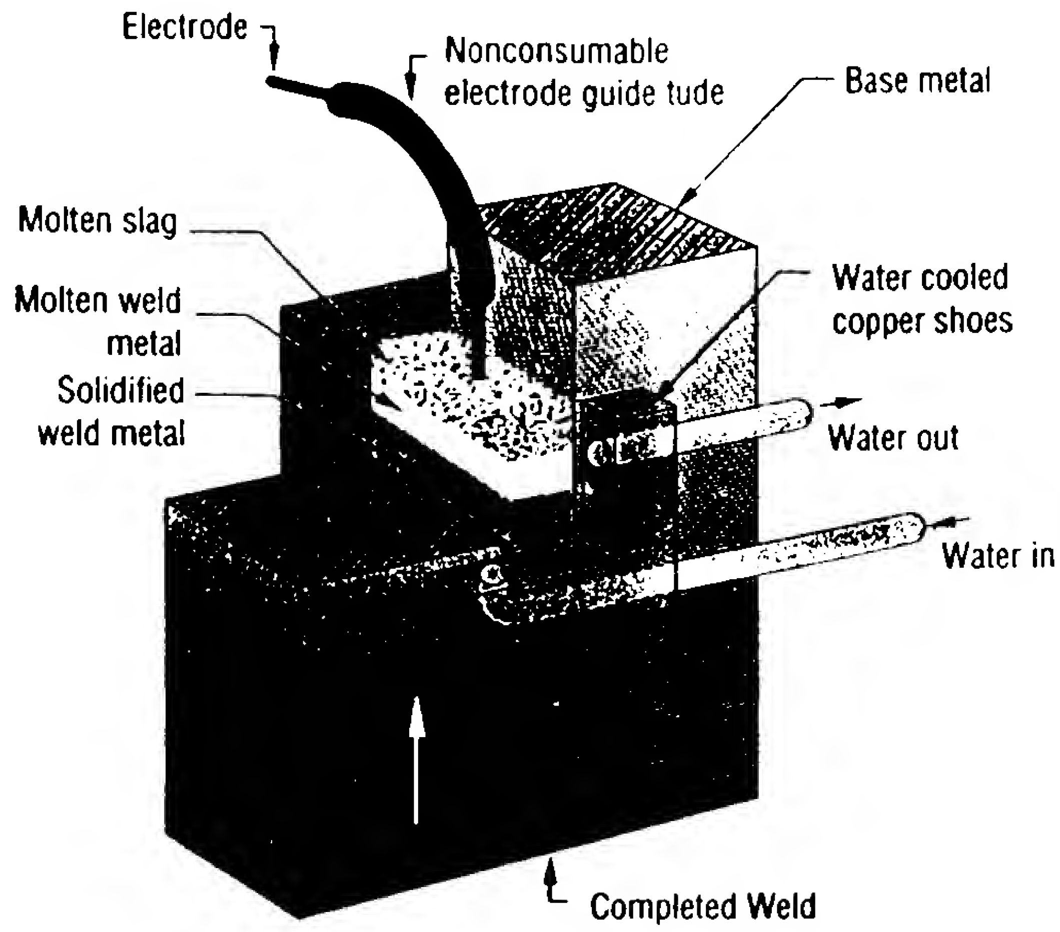


Figure 3.33, Electroslag Welding

ESW is used when very heavy sections are being joined. It is essentially limited to the welding of carbon steels in thicknesses greater

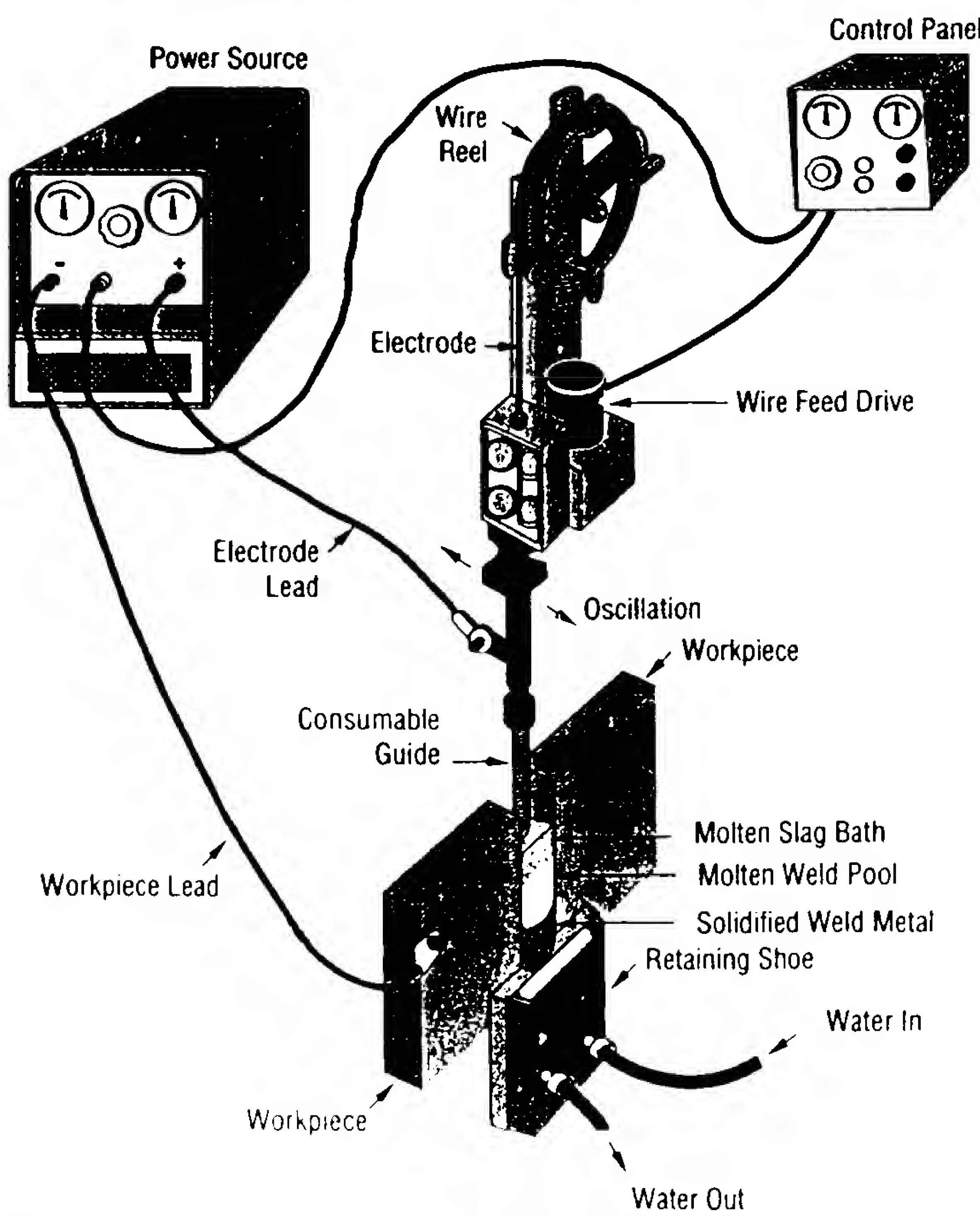


Figure 3.34 - Electroslag Welding Equipment

than 3/4 inch. So, only industries dealing wi heavy weldments have any real interest in ES\ Figure 3.34 shows an ESW equipment setup.

The major advantage of ESW is its hi deposition rate. If single electrode welding not fast enough, then multiple electrodes can used. In fact, metal strip can be used instead wire to increase the deposition rate even mo Another benefit is that there is no special joi preparation required. In fact, a rough, flame c surface is satisfactory for this method. Sin the entire thickness of the joint is fused in single pass, there is no tendency for any angul distortion to occur during or after welding, alignment is easily maintained.

The primary limitation of ESW is t extensive time required to set up and get rea to weld. There is a tremendous amount of tir and effort required to position the workpiec and guides before any welding takes plac That is why ESW is not economical f thinner sections, even though the depositi rate is quite high.

The ESW process has associated with several inherent problems. When the problems arise, they can be of maj proportions. Gross porosity can occur d to wet flux or the presence of a leak in o of the water cooled shoes. Since electrosl welding resembles a casting process many respects, there is a possibility getting centerline cracks due to weld me shrinkage. Also, due to the tremendo amount of heating, there is a tendency f grain growth in the weld metal. These lar grains may result in degradation of t weldment's mechanical properties. Bad cold temp - good for Hot Tep

Oxyacetylene Welding (OAW)

The next process is oxyacetyle welding. While the term 'oxyfuel weldir is also used, acetylene is the only fuel g capable of producing high enou

temperatures for effective welding. With OAW, the energy for welding is created by a flame, so this process is considered to be a chemical welding method. Just as the heat is provided by a chemical reaction, the shielding for oxyacetylene welding is accomplished by this flame as well. Therefore, no flux or external shielding is necessary. Figure 3.35 illustrates the process being applied with filler metal added from some external source.

The equipment for oxyacetylene welding is relatively simple. A typical setup is shown in Figure 3.36. It consists of several parts: oxygen tank, acetylene tank, pressure regulators, torch, and connecting hoses. The oxygen cylinder is a hollow, high pressure container capable of withstanding a pressure of approximately 2200 psi. The acetylene cylinder on the other hand, is filled with a porous material similar to cement.

Acetylene exists in the cylinder dissolved in liquid acetone. Care must be taken since gaseous acetylene is extremely unstable at pressures exceeding 15 psi and an explosion could occur even without the presence of oxygen. Since the acetylene cylinder contains a liquid it is important that it remains upright to prevent spillage.

Each cylinder has attached to its top a pressure regulator which reduces the high internal tank pressure to working pressures. Hoses then connect these regulators to the torch. The torch includes a mixing section where the oxygen and acetylene combine to provide the necessary mixture. The ratio of these two gases can be altered by the adjustment of two separate control valves. Normally, for carbon steel welding, they are adjusted to provide a mixture, which is referred to as a neutral flame. A higher amount of oxygen will create an oxidizing flame and a higher amount of acetylene will produce a carburizing flame. After the gases are mixed, they flow through a detachable tip.

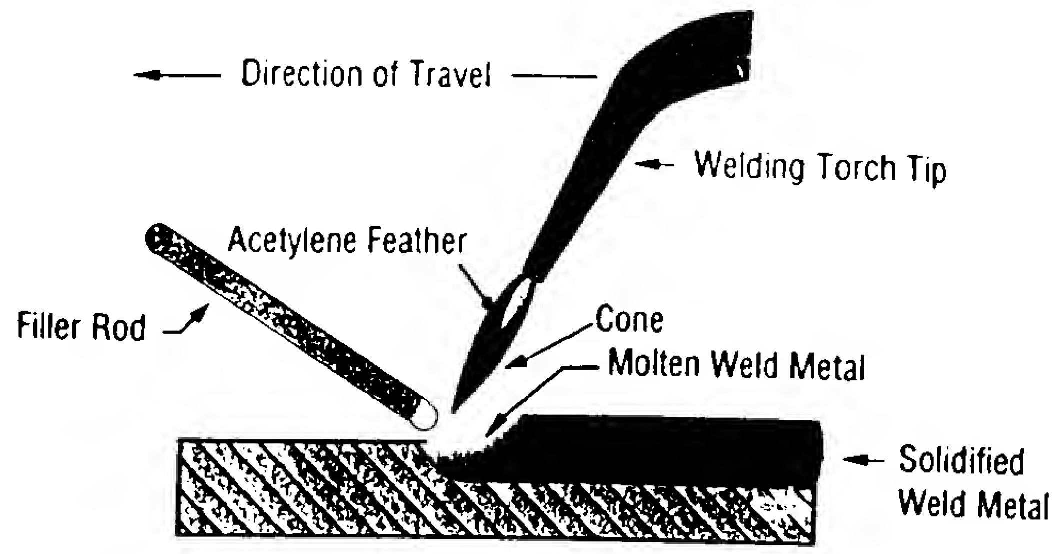


Figure 3.35 - Oxyacetylene Welding

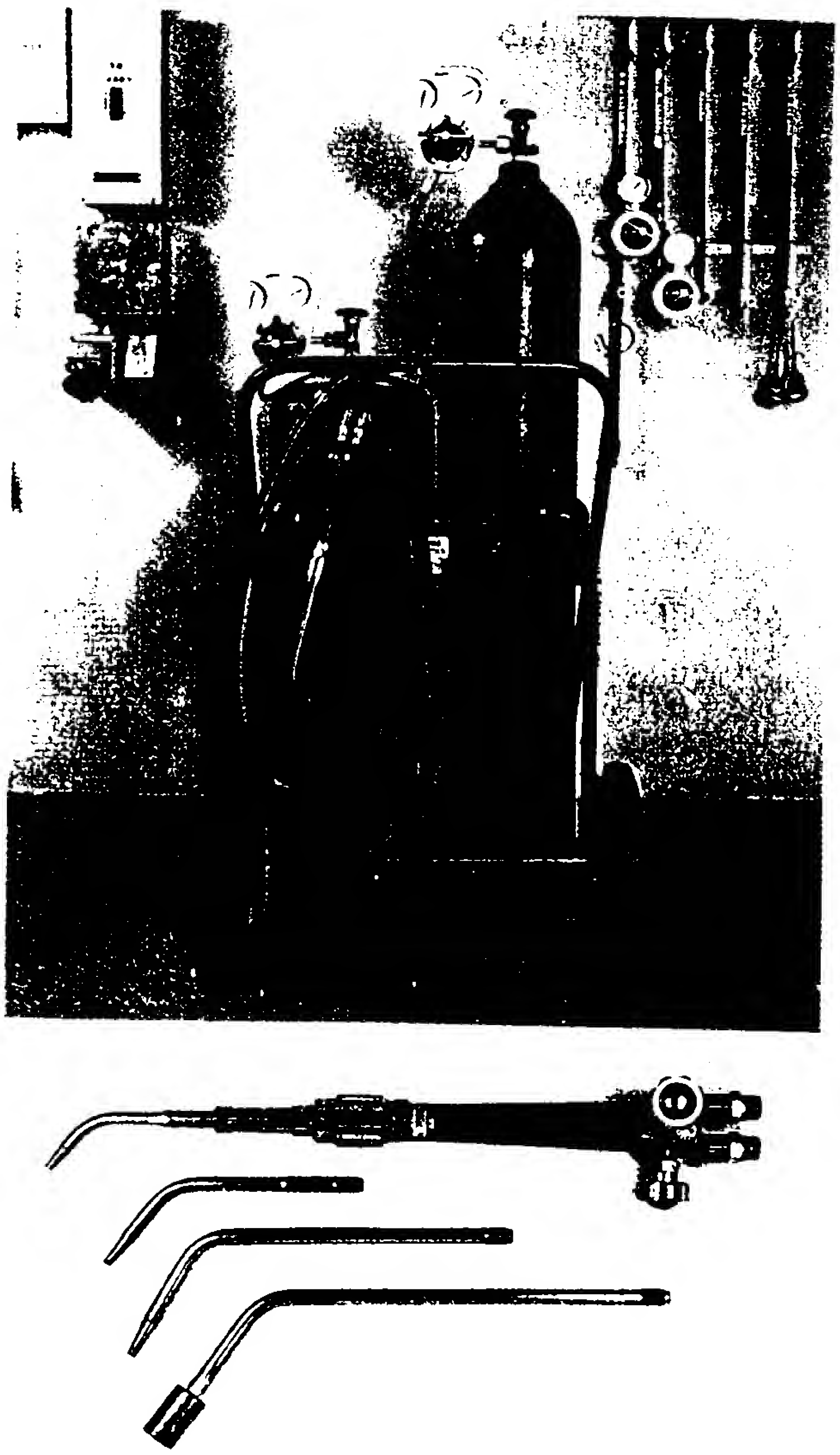


Figure 3.36 Oxyacetylene Welding Equipment

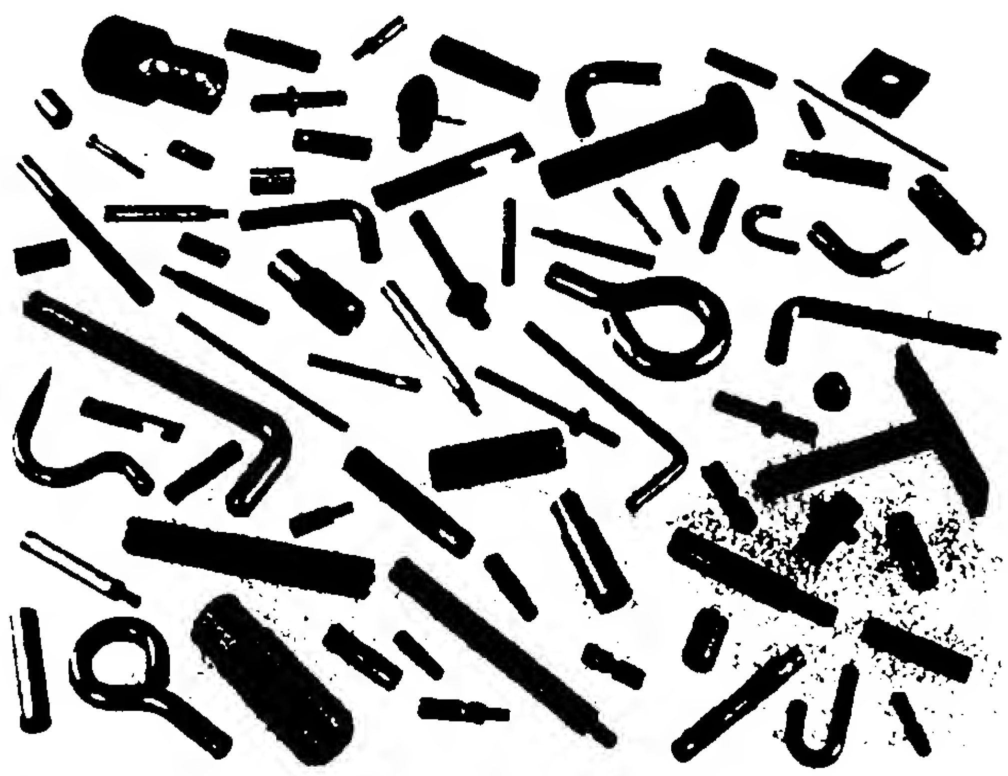


Figure 3.39 - Some Typical Stud and Fastener Configurations Available for Stud Welding

some configuration which can be held in the gun's chuck.

SW has two possible discontinuities. They are lack of 360° flash, and incomplete fusion at the interface. Both are caused by improper machine settings or an insufficient ground connection. Presence of water or heavy rust or mill scale on the base metal surface could also affect the resulting weld quality.

Laser Beam Welding (LBW) Possible 3 TQ.

A laser is a device that produces a concentrated coherent light beam by stimulated electronic or molecular transitions to lower energy levels. Laser is an acronym for light amplification by stimulated emission of radiation. Coherent means that all the light waves are in phase.

In practice, a laser device consists of a medium placed between the end mirrors of an optical resonator cavity. When this medium is "pumped" (i.e., excited) to the point where a population inversion occurs, a condition wherein the majority of active atoms (or molecules) in this medium are put into a higher-than-normal energy state, a source of coherent light that can then reflect back and forth between the end mirrors of the cavity will be provided. This results in a cascade effect being induced which will cause the level of this coherent light to reach a threshold point (i.e., the point at which the gain in light amplification being produced begins to exceed any losses in light that might simultaneously be occurring), thereby allowing the device to start to emit a beam of laser light.

From an engineering standpoint, a laser is an energy conversion device that simply transforms energy from a primary source (electrical, chemical, thermal, optical, or nuclear) into a beam of electromagnetic radiation at some specific frequency (ultraviolet, visible, or infrared). This transformation is facilitated by certain solid, liquid, or gaseous mediums which, when excited on either a molecular or atomic scale (by various techniques), will produce a very coherent and relatively monochromatic (i.e., exhibiting a fairly singular frequency) form of light - a beam of laser light. Because they are coherent and monochromatic, both low-power and high-power laser light beams have a very low divergence angle. Thus they can be transported over relatively large distances before being highly concentrated (through the use of either transmissive or reflective-type focusing optics) to provide the level of beam power density needed to do a variety of material processing tasks such as welding, cutting, and heat treating.

The first laser beam was produced in 1960 using a ruby crystal pumped by a flash lamp. Solid-state lasers of this type produce only short pulses of light energy, and at repetition frequencies limited by heat capacity of the crystal. Consequently, even though individual pulses do exhibit instantaneous peak power levels in the megawatt range, pulsed ruby lasers are limited to low average power output levels. Both pulsed and continuously operating solidstate lasers, capable of welding and cutting thin sheet metal, are currently commercially

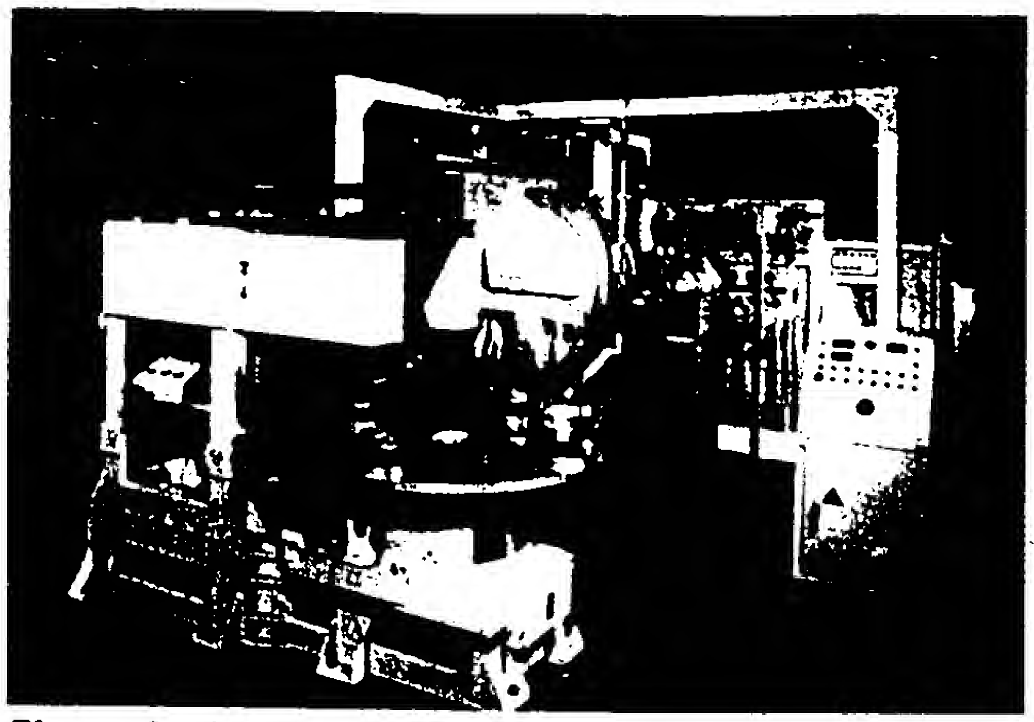


Figure 3.40 - Production System Showing a CO_2 Laser Combined with a Rotary Work Table

available. Many of the latter utilize neodymium-doped, yttrium aluminum garnet (Nd-YAG) crystal rods to produce a continuous, monochromatic beam output in the 1 to 2 kW power range.

Electrically pumped, pulsed and continuous wave (CW) gas lasers of the ac, dc and rf excited variety have also been developed. Thus carbon dioxide (CO_2) lasers, with beam power outputs of up to 25 kW, are commercially available today, and are in use for a wide variety of industrial material processing tasks. Such lasers are capable of providing full penetration, single-pass welds in steel up to 1 - 1 /4 in. (32 mm) thick.

Laser Beam Welding (LBW) is a fusion joining process that produces coalescence of

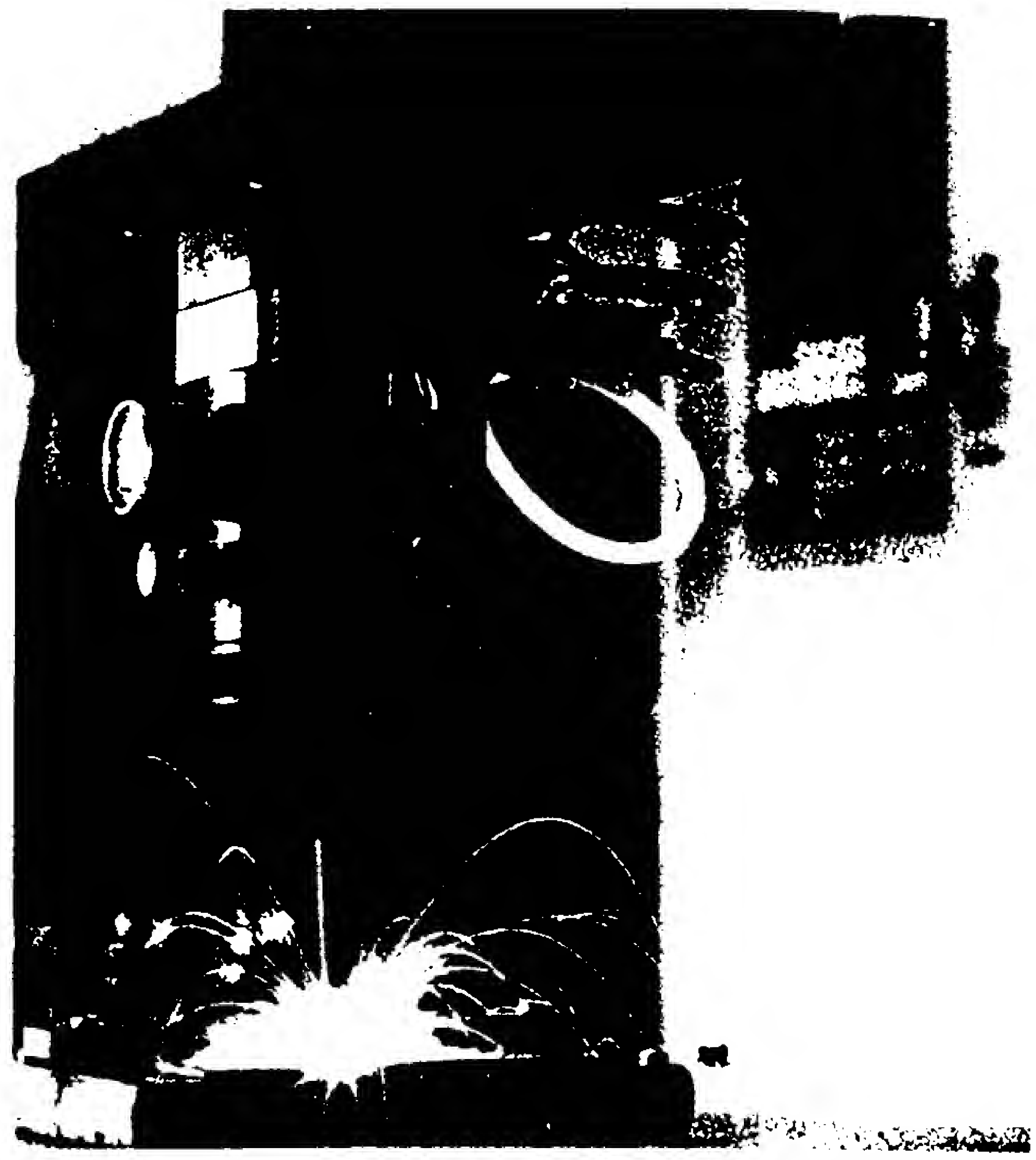


Figure 3.42 - Laser Weld Being Made on 1/8 in. (3.2 mm) Thick Type 304 Stainless Steel

materials with the heat obtained from a concentrated beam of coherent, monochromatic light impinging on the joint to be welded. In the LBW process, the laser beam is directed by flat optical elements, such as mirrors, and then focused to a small spot (for high-power density) at the workplace using either reflective focusing elements or lenses. LBW is a noncontact process, and thus requires no pressure be applied. Inert gas shielding is generally

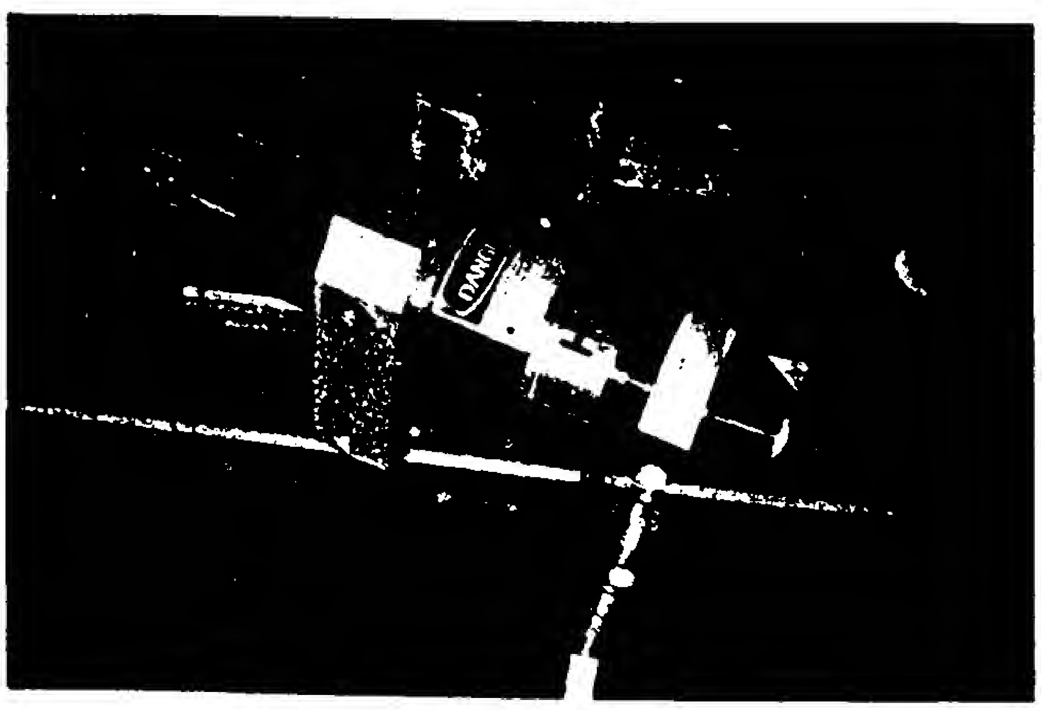


Figure 3.41 - Laser Beam Welding Gun

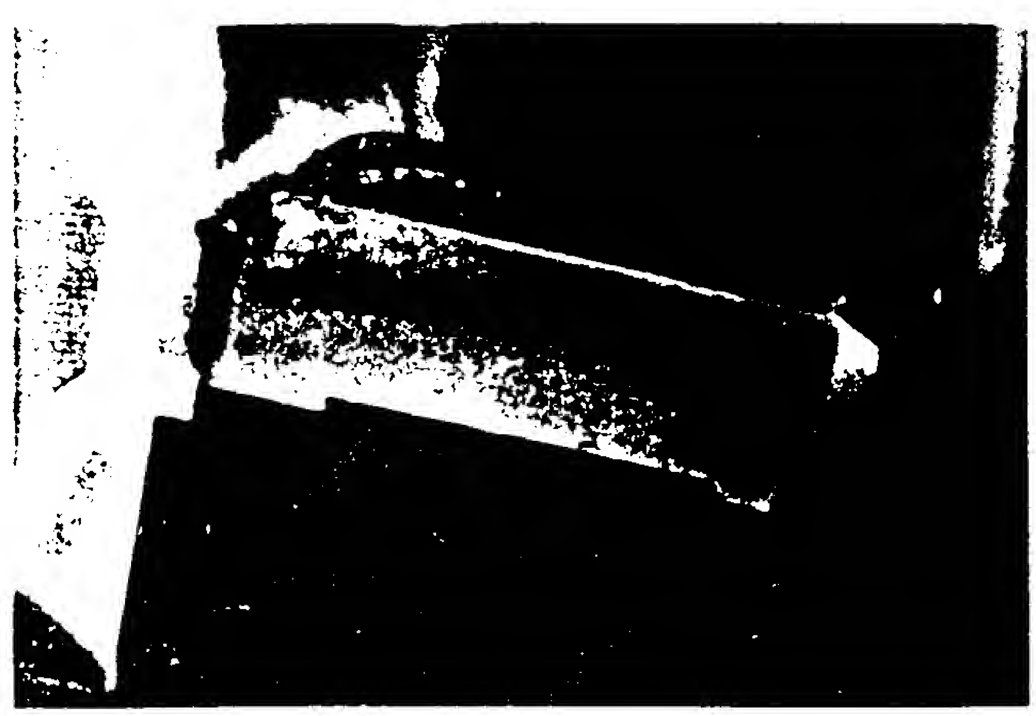


Figure 3.43 - Cross Section of a Laser Beam Weld Joining a Boss to a Ring

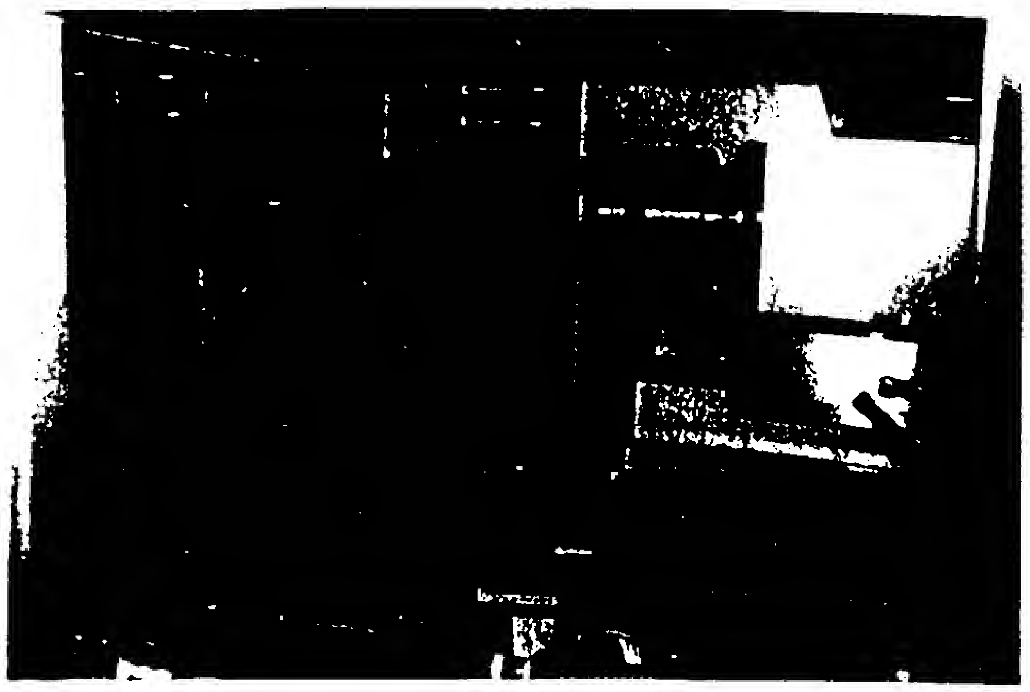


Figure 3.44 - Production Welding System for Automotive Transmission Components

employed to prevent oxidation of the molten puddle, and filler metal may occasionally be used.

As described above, the lasers predominantly being used for industrial material processing and welding tasks are the 1.06 μm wavelength YAG laser and the 10.6 μm wavelength $C0_2$ laser, with the active element most commonly employed in these two varieties of lasers being the neodymium (Nd) ion, and the $C0_2$ molecule (respectively).

Major advantages of laser beam welding include the following:

- Heat input is close to the minimum required to fuse the weld metal; thus, metallurgical effects in heat-affected zones are reduced, and heat-induced workpiece distortion is minimized.
- Singlepass laser welding procedures have been qualified in materials up to 1 - 1/4 in. (32 mm) thick, thus allowing the time to weld thick sections to be reduced and the need for filler wire (and elaborate joint preparation) to be eliminated.
- No electrodes are required; welding is performed with freedom from electrode contamination, indentation, or damage from high resistance welding currents. Because LBW is a noncontact process, distortion is minimized and tool wear essentially eliminated.
- Laser beams are readily focused, aligned, and directed by optical elements. Thus the laser can be located at a convenient distance from the workpiece, and redirected around tooling and obstacles in the workpiece. This permits welding in areas not easily accessible with other means of welding.
- The workpiece can be located and hermetically welded in an enclosure that is evacuated or that contains a controlled atmosphere.
- The laser beam can be focused on a small area, permitting the joining of small, closely spaced components with tiny welds.
- A wide variety of materials can be welded, including various combinations of different type materials.
- The laser can be readily mechanized for automated, high-speed welding, including numerical and computer control.
- Welds in thin material and on small diameter wires are less susceptible to burn-back than is the case with arc welding.
- Laser welds are not influenced by the presence of magnetic fields, as are arc

and electron beam welds; they, also tend to follow the weld joint through to the root of the workpiece, even when the beam and joint are not perfectly aligned.

- Metals with dissimilar physical properties, such as electrical resistance, can be welded.
- No vacuum or X-ray shielding is required.
- Aspect ratios (i.e., depth-to-width ratios) on the order of 10:1 are attainable when the weld is made by forming a cavity in the metal,such as in keyhole welding.
- The beam can be transmitted to more than one work station, using beam switching optics, thus allowing beam time sharing.

Laser Beam Welding has certain limitations when compared to other welding methods, among which are the following:

- Joints must be accurately positioned laterally under the beam and at a controlled position with respect to the beam focal point.
- When weld surfaces must be forced together mechanically, the clamping mechanisms must ensure that the final position of the joint is accurately aligned with the beam impingement point.
- The maximum joint thickness that can be laser beam welded is somewhat limited. Thus weld penetrations of much greater than 0.75 in. (19 mm) are not presently considered to be practical production LBW applications.
- The high reflectivity and high thermal conductivity of some materials, such as aluminum and copper alloys, can affect their weldability with lasers.
- When performing moderate-to-high power laser welding, an appropriate plasma control device must be employed to ensure weld reproducibility is achieved.
- Lasers tend to have a fairly low energy conversion efficiency, generally less than 10 percent.
- As a consequence of the rapid solidification characteristic of LBW, some weld porosity and brittleness can be expected.
- Equipment is expensive.

Electron Beam Welding

Since electron beam welding (EBW) was initially used as a commercial welding process in the late 1950's, the process has earned a broad acceptance by industry. During this initial period of commercial application, the process was limited strictly to operation in a high vacuum chamber. However, a system was soon developed that required a high vacuum only in the beam generation portion. This permitted the option of welding in either a medium vacuum chamber or a nonvacuum environment. This advancement led to its acceptance by the commercial automotive and consumer product manufacturers. As a consequence, EBW has been employed in a broad range of industries worldwide.

EBW is a fusion joining process that produces coalescence of materials with heat obtained by impinging a beam composed

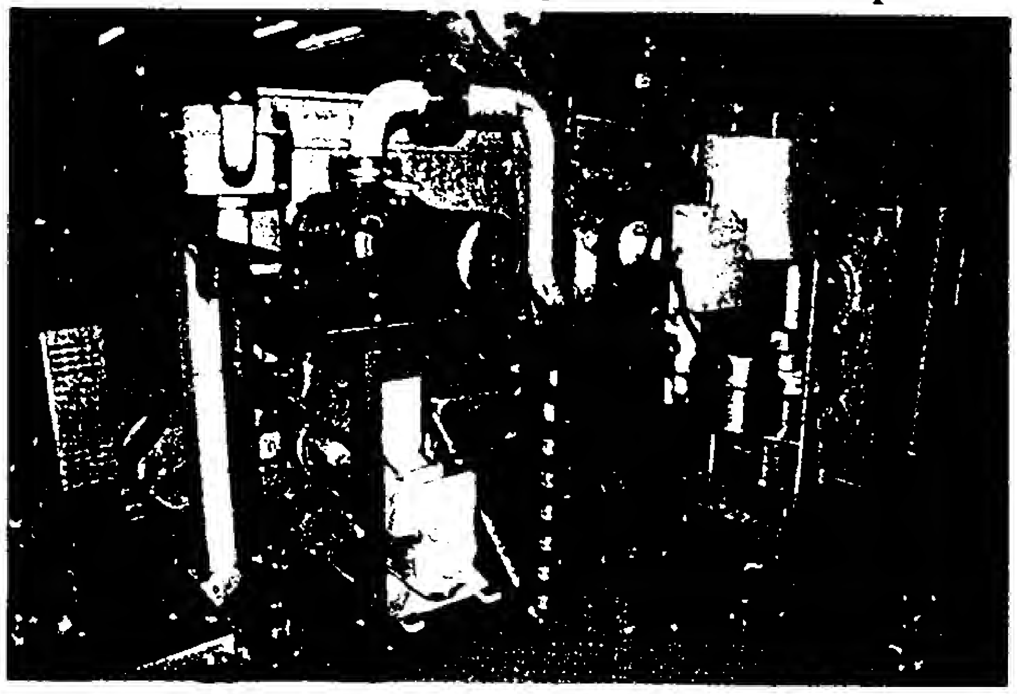


Figure 3.45 - Exterior View of an Electron Beam Vacuum Pump

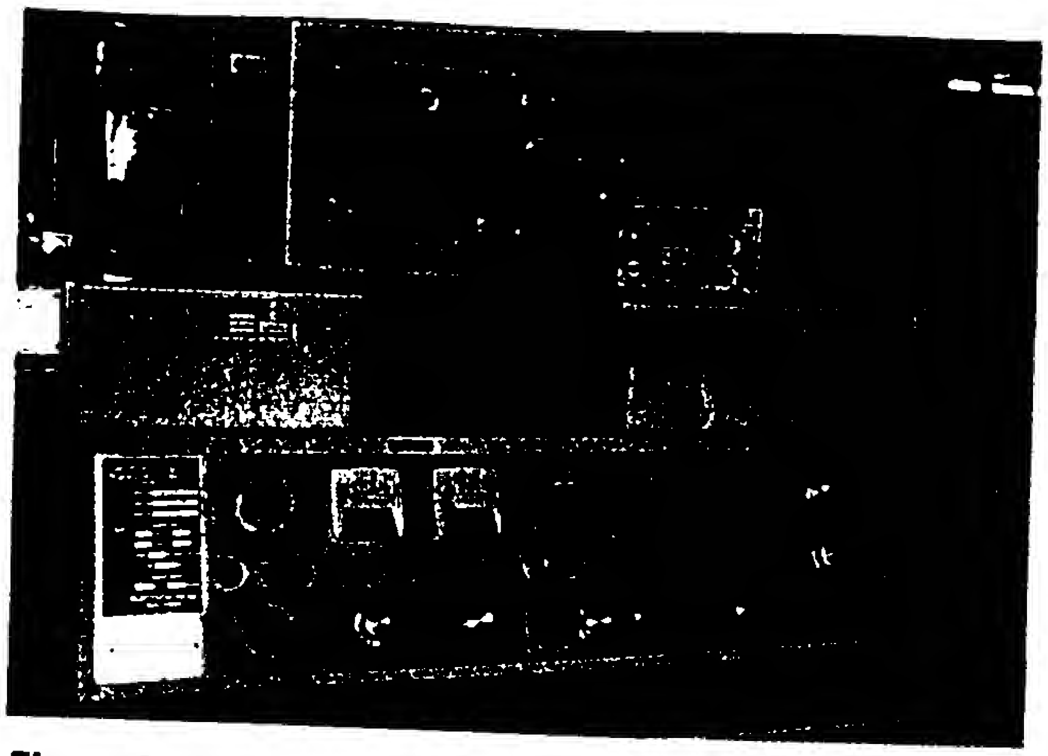


Figure 3.46 - Electron Beam Welding Control Panel

primarily of high-energy electrons onto the joint to be welded. Electrons are fundamental particles of matter, characterized by a negative charge and a very small mass. For EBW they are raised to a high-energy state by being accelerated to velocities in the range of 30 to 70 percent of the speed of light.

The beam of electrons is created using an electron gun that typically contains some type of thermionic electron emitter (normally referred to as the gun "cathode" or "filament"), a biasing control electrode (normally referred to as the gun "grid" or "grid cup"), and an anode. Various supplementary devices, such as focus and deflection coils, are also provided to focus and deflect this beam.

Figure 3.47 - Electron Beam Welding Machine Designed for Joining Bimetallic Strip

The heart of the electron beam welding process is the electron beam gun/column assembly. Electrons are generated by heating a negatively charged emitting material to its thermionic emission temperature range, thus causing electrons to "boil off" this emitter or cathode and be attracted to the positively charged anode. The precisely configured grid or bias cup surrounding the emitter provides the electrostatic field geometry that then simultaneously accelerates and shapes these electrons into the beam. The beam then exits the gun through an opening in the anode continues on toward the workpiece. Once the beam exits

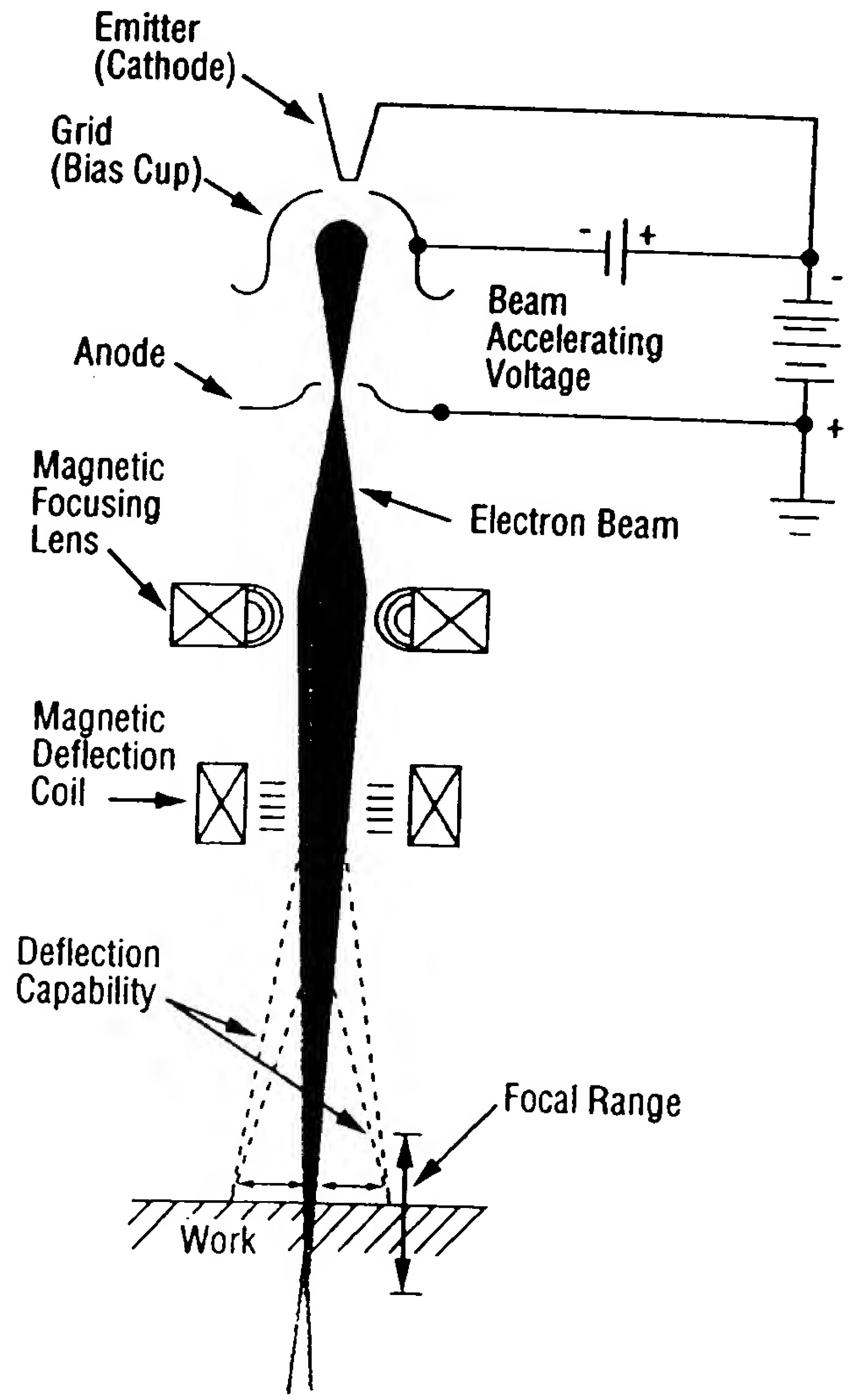


Figure 3.48 - Simplified Representation of a Triode Electron Beam Gun Column

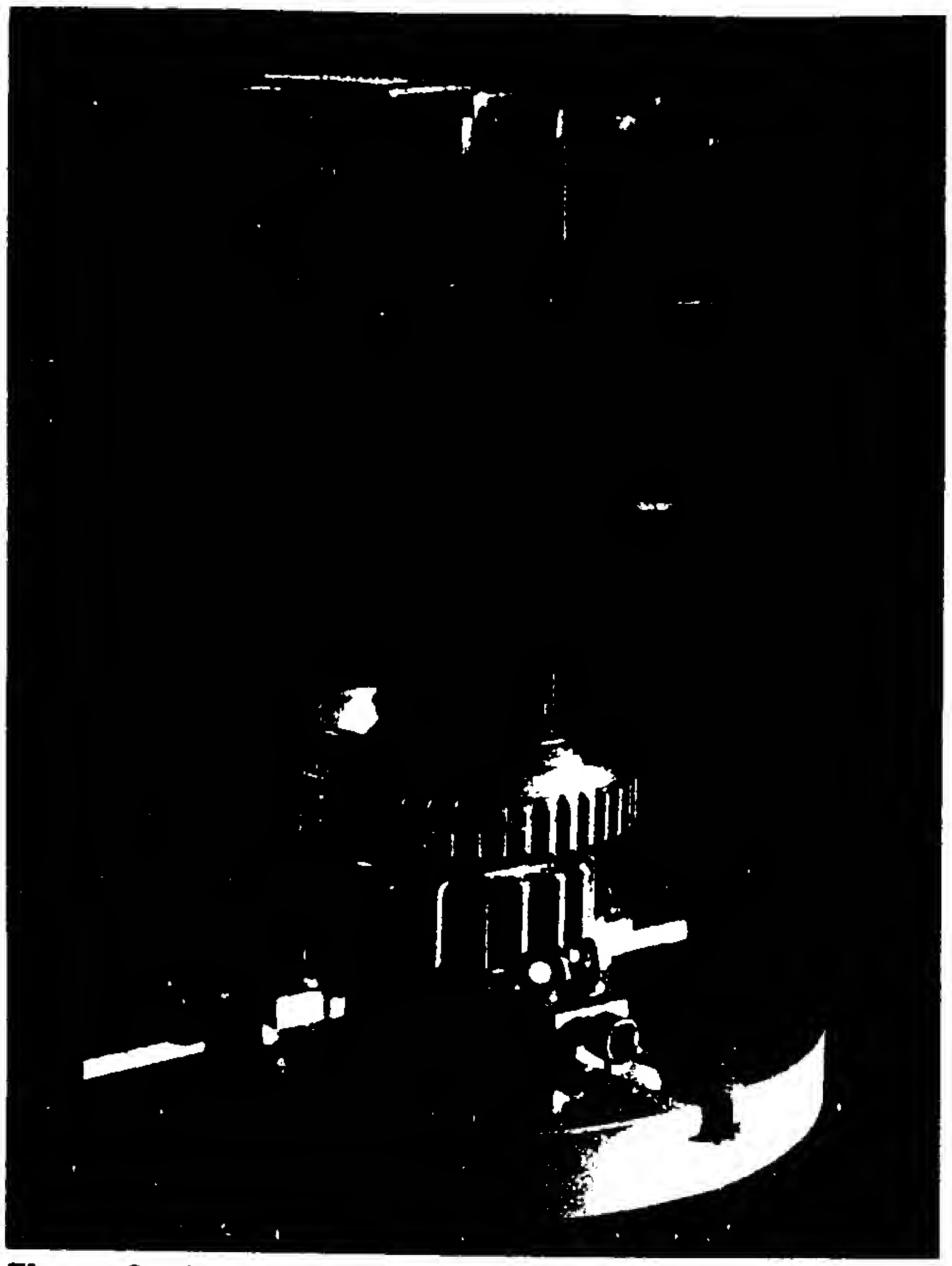


Figure 3.49 - Electron Beam Welding a Gear in Medium Vacuum

from the gun, it will gradually broaden with distance. This divergance results from the fact that all the electrons in the beam have some amount of radial velocity, due to their thermal energy, and in addition, all experience some degree of mutual electrical repulsion. Therefore, in order to counteract this inherent divergence effect, an electromagnetic lens system is used to converge the beam, which focuses it into a small spot on the workpiece. The beam divergence and convergence angles are relatively small, which gives the concentrated beam a usable focal range, or "depth-of-focus", extending over a distance of an inch or so.

In practice, the rate of energy input to the weld joint is controlled by the following four basic variables:

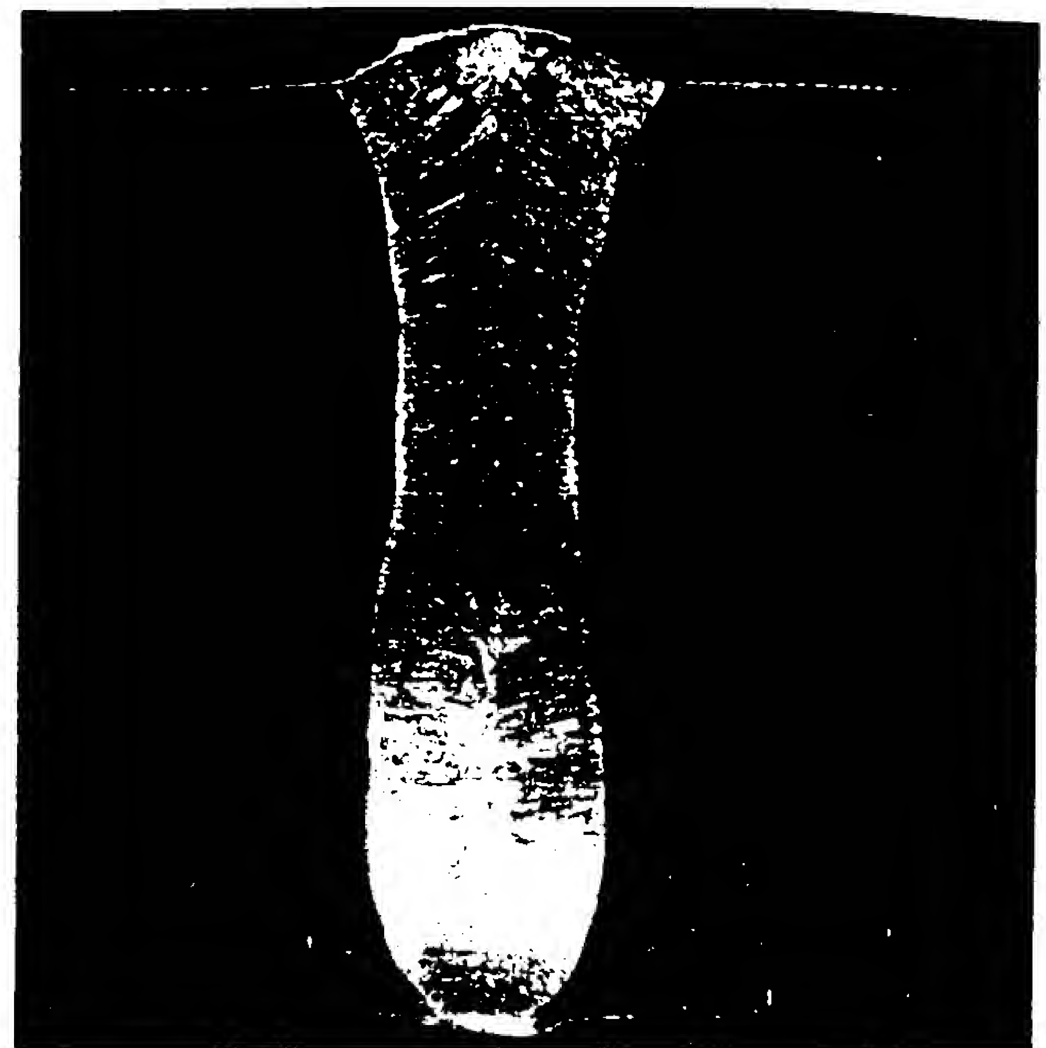


Figure 3.50 - Cross Section of a Nonvacuum Electron Beam Weld in 3/4 in. (19mm) Stainless Steel Plate

- The number of electrons per second being impinged on the workpiece (beam current)
- The magnitude of velocity of these electrons (beam accelerating voltage)
- The degree to which this beam is concentrated at the workpiece (focal beam spot size)
- The travel speed with which the workpiece or electron beam is being moved (welding speed)

At power densities on the order of 10^5 W/in.^{2} (1.55 x 10^2 W/mm^2), and greater, the electron beam is capable of instantly penetrating into a solid workpiece or a butt joint and forming a vapor capillary (or "keyhole") which is surrounded by molten metal. As the beam advances along the joint, molten metal from the forward portion of the keyhole flows around its periphery and solidifies at the rear to form weld metal. In most applications, the weld penetration formed is much deeper than it is wide, and the heat-affected zone produced is very narrow. For example, the width of a butt

weld in 0.5 in. (13mm) thick steel plate may be as small as 0.030 in. (0.8 mm) when made in a vacuum. This stands in remarkable contrast to the weld zone produced in arc and gas welded joints, where penetration is achieved primarily through conduction melting.

An electron beam can be readily moved about by electromagnetic deflection. This allows specific beam spot motion patterns (circles, ellipses, bow tie shapes, etc.) to be generated on the surface of a workpiece when an electronic pattern generator is used to drive the deflection coil system. This deflection capability can, in certain instances, also be used to provide beam travel motion. In most instances, however, deflection is used to adjust the beam to-joint alignment, or to apply a deflection pattern. This deflection modifies the average power density being input to the joint, and results in a change in the weld characteristics achieved. However, as previously noted, care must always be taken when using any type of beam deflection to ensure that the beam angle of incidence does not adversely affect the final weld results. It especially must not cause part of the weld joint to be missed.

Electron beam welding has unique performance capabilities. The high-quality environment, high-power densities, and outstanding control solve a wide range of joining problems. The following are advantages of electron beam welding:

- The EBW directly converts electrical energy into beam output energy. Thus the process is extremely efficient.
- Electron beam weldments exhibit a high depth-to-width ratio. This feature allows for single-pass welding of thick joints.
- The heat input per unit length for a given depth of penetration can be much lower than with arc welding. The resulting narrow weld zone results in low distortion, and fewer deleterious thermal effects.
- A high-purity environment (vacuum) for welding minimizes contamination of the metal by oxygen and nitrogen.
- The ability to project the beam over a distance of several feet in vacuum often allows welds to be made in otherwise inaccessible locations.
- Rapid travel speeds are possible because of the high melting rates associated with this concentrated heat source. This reduces welding time and increases productivity and energy efficiency.
- Reasonably square butt joints in both thick and relatively thin plates can be welded in one pass without filler metal addition.
- Hermetic closures can be welded with the high- or medium-vacuum modes of operation while retaining a vacuum inside the component.
- The beam of electrons can be magnetically deflected to produce various shaped welds; and magnetically oscillated to improve weld quality or increase penetration.
- The focused beam of electrons has a relatively long depth of focus, which will accommodate a broad range of work distances.
- Full penetration, single-pass welds with nearly parallel sides, and exhibiting nearly symmetrical shrinkage, can be produced.
- Dissimilar metals and metals with high thermal conductivity such as copper can be welded.

Some of the limitations of electron beam welding are as follows:

- Capital costs are substantially higher than those of arc welding equipment. Depending on the volume of parts to be

produced, however, the final "per piece" part costs attainable with EBW can be highly competitive.

- Preparation for welds with high depth-to-width ratio requires precision machining of the joint edges, exacting joint alignment, and good fit-up. In addition, the joint gap must be minimized to take advantage of the small size of the electron beam. However, these precise part-preparation requirements are not mandatory if high depth-to-width ratio welds are not needed.
- The rapid solidification rates achieved can cause cracking in highly constrained, low ferrite stainless steel.
- For high and medium vacuum welding, work chamber size must be large enough to accommodate the assembly operation. The time needed to evacuate the chamber will influence production costs.
- Partial penetration welds with high depth-to-width ratios are susceptible to root voids and porosity.
- Because the electron beam is deflected by magnetic fields, nonmagnetic or properly degaussed metals should be used for tooling and fixturing close to the beam path.
- With the nonvacuum mode of electron beam welding, the restriction on work distance from the bottom of the electron beam gun column to the work will limit the product design in areas directly adjacent to the weld joint.
- With all modes of EBW, radiation shielding must be maintained to ensure that there is no exposure of personnel to the x-radiation generated by EB welding.
- Adequate ventilation is required with nonvacuum EBW, to ensure proper removal of ozone and other noxious gases formed during this mode of EB welding.

Several T.Q.'s

BRAZING PROCESSES

Now that the welding processes have been discussed, we will now turn our attention to brazing. Brazing differs from welding in that brazing is accomplished without any melting of the base metals. The heat is only sufficient for the melting of the filler metal. Another joining process, soldering, is similar in that it too only requires melting of the filler metal to create a bond. Brazing and soldering are differentiated by the temperature at which the filler metal melts. Filler metals melting above 840°F (450° C) are considered braze materials, while those melting below this temperature are used for soldering. Therefore, the common term "silver soldering" is actually incorrect, because silver brazing filler metal melts above 840°F.

Even though the base metals are not melted and there is no fusion between the filler metal and base metals, a bond is created which has substantial strength. When properly applied, the braze joint can develop a strength equal to or greater than the base metal even though the braze material may be much weaker than the base metal. This is possible because of two factors.

First, the braze joint is designed to have a large surface area. Also, the clearance, or gap, between the two pieces to be joined is kept to a minimum. Gaps greater than about 0.010 in. (0.25 mm) may result in a joint having substantially reduced strength. Some typical braze joint configurations are shown in Figure 3.51. As can be seen, all of these joints have relatively large surface areas and tight gaps between parts.

To perform brazing, one of the most important steps is to thoroughly clean the joint surfaces. If the parts are not sufficiently clean,